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Development of a Thickness Design Procedure for Stabilized Layers Under Rigid Airfield Pavements

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Final Report

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U.S. Department of Transportation
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NOTICE

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16. Abstract

The results of an analysis of two rigid layer pavement systems are presented. The outcome of the study resulted in the development of a design procedure which can account for the materials properties of the stabilized materials layer. The study employed the use of elastic layer theory and regression analysis to predict the interior stress under aircraft loadings. Equivalent interior stress is used as the design criteria such that a single-layer rigid pavement on subgrade is equated to a two-layer system with a cement-treated base course and a portland cement concrete surface. The comparison of the developed procedures to the existing procedures show both allowable decreases and increases in the thickness of the portland cement concrete layer. The design procedure is an iterative process and has been computerized using IBM Basic. Two programs, the CTBDES and the CTBEVAL, are included in the report.

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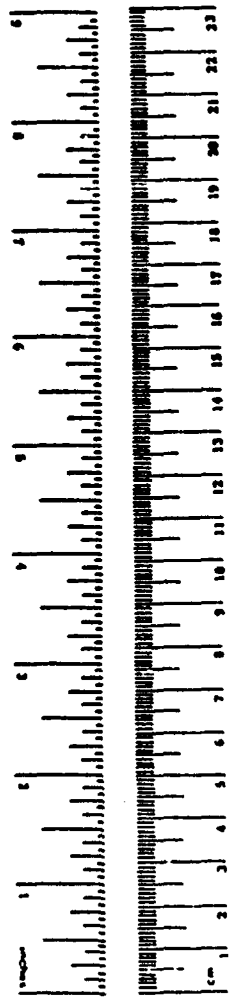
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

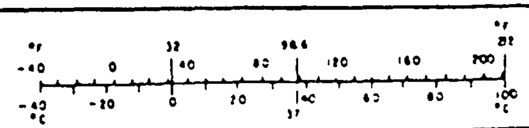
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13 10 286.



Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report was sponsored by the US Department of Transportation, Federal Aviation Administration (FAA), under Interagency Agreement No. DTFA01-81-Y-10555. Mr. H. Tomita was the FAA Technical Monitor.

The study was performed by Soil and Materials Engineers, Inc., under Broad Agency Announcement Contract No. DACA-39-87-C-0017. The report was prepared by Dr. S. D. Kohn and Mr. C. A. Gemayel. The US Army Engineer Waterways Experiment Station (WES) Technical Monitor was Mr. D. R. Alexander, Systems Analysis Branch (SAB), Pavement Systems Division (PSD), Geotechnical Laboratory (GL). Mr. J. W. Hall, Jr., was Chief, SAB; Mr. H. H. Ulery, Jr., was Chief, PSD; and Dr. W. F. Marcuson III was Chief, GL, WES during preparation of the report. The report was edited by Ms. Odell F. Allen, Information Products Division, Information Technology Laboratory.

The Commander and Director of WES during the preparation of this report was COL Larry B. Fulton, EN. The Technical Director was Dr. Robert W. Whalin.

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INTRODUCTION

Background

Current airfield pavement design procedures do not include a methodology to determine the thickness of a stabilized base course material. In October of 198_, a Federal Aviation Administration (FAA) report[2] reviewing its 1978 airfield pavement design guide was published. This report was primarily concerned with evaluating the existing FAA pavement design procedures for high traffic volume pavements (pavements receiving over 100,000 annual departures). In the design review and data collection phases of this project, it was pointed out that there was no uniform method employed in the design of the pavement sections with regard to the thickness determination of the stabilized base layers. Several pavement sections were designed using detailed theoretical analysis, and others were designed using empirical methods to determine the thickness of the stabilized base system. Test sections were also used in some designs to verify the assumptions of the theoretical analysis.

Most of these facilities were constructed in the early 1970's. Since that time, the FAA has published Advisory Circular 150/5320-6C, dated December 7, 1978. This circular includes a requirement for stabilized bases (when gross aircraft weight exceeds 100,000 lb) and presents a methodology to adjust the K-value of the subgrade for the addition of stabilized base. This method is easily applied to determine the thickness of the concrete slab required. However, determination of the stabilized base thickness is left to an iteration process. A suggestion is presented in the design guide that the thickness of the base course be as thick as the required slab. This statement has often been interpreted in an incorrect fashion by some designers. The statement has been taken literally where a concrete thickness will be determined for a given K-value and then a base course thickness of the required slab designed into the project. This is done without the next iteration on the base course to determine a new K-value.

Other problems identified in the current approach are as follows:

<u>a.</u> There is no adjustment for the quality of stabilized materials either in terms of modulus of elasticity or modulus of rupture.

<u>b.</u> The table adjusts the K-value to a maximum value of 500 pci beyond which there is no adjustment.

c. The chart used to adjust the K-value of the subgrade is currently truncated at a stabilized base thickness of 12 in. This is not sufficient for high- volume airfield pavements.

Purpose

The purpose of this study was to develop a design procedure for the selection of the thickness of a stabilized base course material for rigid airfield pavements. The design method was developed to account for the materials properties of the stabilized base course, and to be completely compatible with the elastic layer analysis being used by the US Army Corps of Engineers.

Scope

The methodology employed in this study is applicable to the design of rigid (portland cement concrete) pavements utilizing cement treated aggregate as the base course material. The program developed has been designed using a single-wheel load, a dual-gear load (Boeing 727), and a dual-tandem gear load (Boeing 767). The use of a mixed traffic equation will allow the procedure to be used in mixed traffic conditions as long as one of the above wheel loads is used as the design wheel load.

The procedure utilizes elastic layer analysis as the theoretical basis of the method. Thus, it is feasible that the method could be extended to other stabilized materials provided that their materials properties are within the boundaries used in this study and that their primary failure mechanism is tensile fatigue.

Organization

Section 2 presents the design considerations including the overall approach to the problem, selection of the design factorial and selection of the stress analysis procedure. Section 3 presents the results of the stress analysis and discusses the relationships of the variables. The stress determination procedures are presented in Section 4.

Sections 5 and 6 present the development of the design procedure, the computer programs, and the comparison of the new method to existing design approaches. Section 7 summarizes the findings and presents conclusions and recommendations for further study.

DESIGN CONSIDERATIONS

Introduction

In order to develop a design procedure that will allow for varying the stabilized materials properties, the relevant constitutive properties and failure mode of the materials need to be identified. In the case of cement treated bases, Williams [11] has identified the modulus of elasticity, modulus of rupture, and flexural fatigue as the critical materials parameters to be utilized in design. Other researchers have identified flexural strain (Mitchell and Chen, Pretorius, Raad) [5,7,8] as the failure parameter. Costigan [1] in his work for the US Air Force used the flexural stress approach. In order to maintain consistency with the current FAA and US Army Corps of Engineers (CE) concrete design procedures, the flexural stress approach was selected for use in this study.

The basic elements of this study are as follows:

a. Identify variables necessary to cover the possible range of materials properties.

b. Select aircraft type to be used in the study.

c. Analyze the stress state for the selected aircraft and materials combinations.

d. Develop the design procedure based on the stress state of the paving layers.

e. Compare new procedure to the existing design scheme.

Thus, the major parameters that must be considered in the design process are:

a. Thickness of the concrete

b. Elastic modulus of the concrete

c. Thickness of the cement treated base (CTB)

d. Elastic modulus of the CTB

e. Elastic modulus of the subgrade

f. Traffic parameters (gear type and load).

The practical range of each of these factors is required to develop a manageable analysis of the tensile stress conditions for combinations of concrete surface and CTB base course layers.

Factorial Selection

A review of the thicknesses of the pavements studied in the high volume traffic design project was performed along with the associated traffic and materials properties data. In addition to this review, several pavement designs were performed to determine typical concrete thickness to define the boundaries of the problem. This synthesis resulted in the following parameters to be included in the factorial:

a. Thickness of the concrete (H_{conc}), in., 8, 10, 14, 22, and 26.

b. Elastic modulus of the concrete (Ec), psi, 4,000,000.

c. Thickness of the CTB (H_{ctb}), in., 4, 8, 10, 14, and 22.

d. Elastic modulus of the CTB (E_{ctb}), ksi., 250, 500, 1,000, and 2,500.

e. Elastic modulus of the subgrade (E_{sub}), psi, 5,000, 10,000, 20,000, and 30,000.

f. Gear types, single wheel, B-727, B-767

g. Frictional Factor of 300 between concrete and CTB and CTB and subgrade.

This resulted in a total of 1,200 cases to analyze the stress state in the concrete and CTB systems.

Selection of Stress Analysis Procedure

The selection of the theoretical analysis procedure to define the stress state in the multilayer system was the next decision point. For a rigid pavement system, there are several analysis procedures available such as Westergaard, finite element methods, or elastic layer theory to analyze the stress state in the pavement structure. Of these approaches, only the Westergaard and finite element procedures can be used to determine the pavement behavior caused by the edge load conditions. However, these methods have not been adopted to the multilayer case with different

interface friction conditions. Finite element methods have been developed which can handle a base course layer; however, the interface condition is preset at full bond or no bond.

Analysis of the non-destructive testing (NDT) data obtained on the high traffic volume pavement project has shown that basin matching program BISDEF provides better estimates of the field deflection basins if the friction value between the layers was varied. This fact in combination with the other factors stated above lead to the use of the "BISAR"[7] elastic layer procedure for use in the stress analysis. BISAR is structured to model frictional interface conditions between layers on a continuous scale.

The disadvantage in using the BISAR system is its inability to handle the edge (or joint) load condition. The inability to handle the edge load condition has been considered a serious drawback to the elastic layer analysis. Parker et al. [6] have overcome this through correlation of edge and interior load conditions. This study uses a slightly different approach which accomplishes the same result. This will be discussed below and in Section 6.

Stress Analysis

As previously mentioned the current FAA design procedures are based on the edge stress loading condition. This is the load condition created when a gear or wheel is placed on a free edge of the slab. In the design procedure a value of 75 percent of the free edge load is used to account for the load transfer between slabs. In order to relate the FAA edge load design to the BISAR elastic layer interior load condition, it was necessary to determine the interior stress condition for the case of a concrete slab on subgrade. For this set of systems, the frictional factor was set to the full slip condition, and the range of thicknesses was changed to 8, 10, 14, 18, 22, and 26 in. over the same subgrade conditions. This resulted in an additional 72 cases to be analyzed. The selection of the full slip case was made to model more closely the slab on a liquid subgrade condition. This condition also provides a measure of safety, since the full slip condition results in greater stress values.

In each of the analysis, the maximum tensile stress in the concrete and the CTB was located. The maximum was also located for the slab-on-grade cases. For the multiple wheel load cases, the search for the maximum tensile stress was performed in several locations. Figure 1 presents the general layer structure and interface conditions used in the analysis, and Figure 2 illustrates the search locations of the multiple wheel assemblies. As shown in the figure, a

rigid subgrade layer was also used. This layer is input so that surface deflections more closely match the field conditions.

The Friction factor of 300 represents a friction between the layers of about 30 percent. The value is a dimensionless value. The BISAR program allows varying the friction factor from 0 to 1000. The 300 value was based on the back calculation of moduli for the pavements studied by Kohn[2].

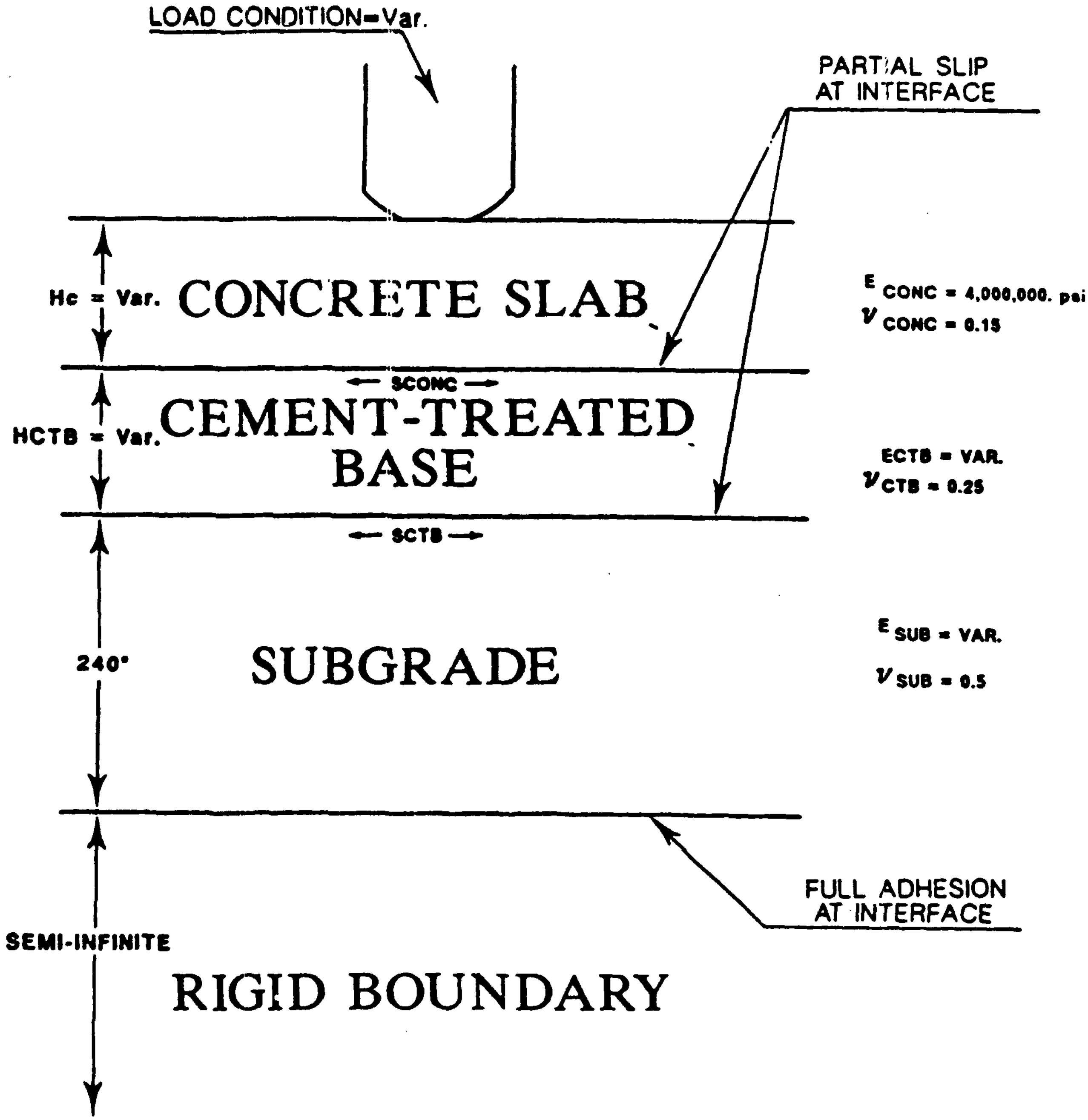
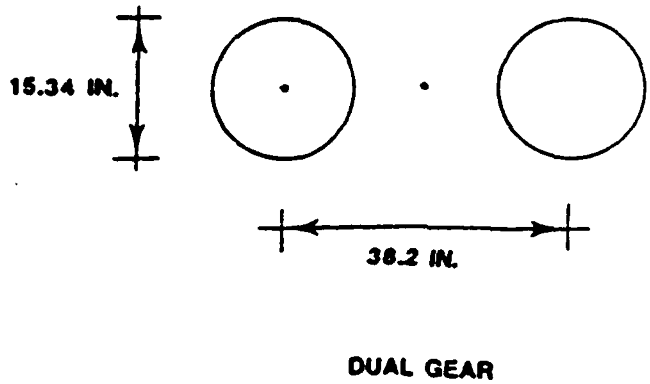


Figure 1. Pavement structure and layer interface conditions used in the stress analysis



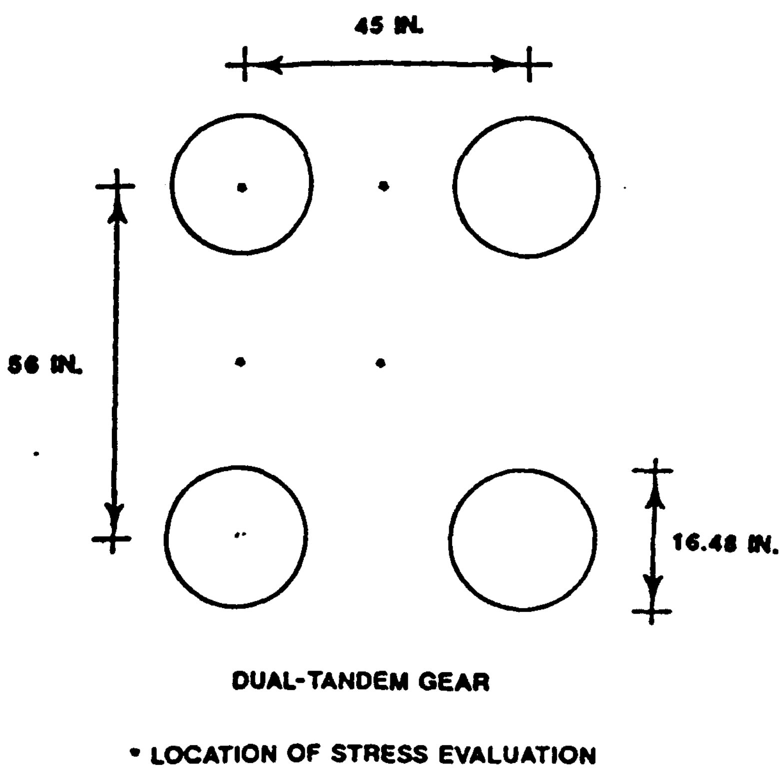


Figure 2. Search locations for the maximum tensile stress for the multiple wheel assemblies

RESULTS OF STRESS ANALYSIS

The results of the 1,272 systems analyzed are presented and discussed in this section. As shown previously in Figure 2, multiple search locations were used in the analysis. The pavement configuration and interface condition were presented in Figure 1.

The resulting maximum tensile stresses are presented in Appendix A. Table A1 is illustrative of the set of results. This table, presented in the appendix, includes the results for the pavements containing the CTB layer. All stresses presented are the maximum radial tensile stress for the condition represented.

In order to initiate the development of the design process, it was already determined that the maximum tensile stress of each layer would be the major design factor.

Prior to starting the analysis procedures, graphic representations of the stress in the concrete (STRC) and stress in the base course (STRB) were prepared. Plots were developed of both the stress factors against each of the major variables. A complete <u>set</u> of graphs is presented in Appendix B. Figures 3 to 22 represent the stress condition for the single wheel load. Figures 3 to 18 represent the mean pavement parameters used in the stress factorial, and Figures 19 to 22 present the conditions at the boundaries of the factorial.

Stress in the Concrete

Figures 3 to 10 present the primary relationships for the stress in the concrete slab. As the curves in the figures show, the relationship between STRC and H_{conc} is certainly a power function. From the theoretical analysis of the condition it is a function of $1/H^2_{conc}$. This can be determined through the review of the Westergaard equations. Scott[9] presents an excellent summary of these equations and other analytical approaches to calculating the tensile stress in a slab resting on either a Winkler (liquid) or elastic foundation.

Some other general observations can be made regarding the stress in the concrete when viewing the plots. The elastic modulus of the subgrade (E_{sub}) alone does not have a major effect on the stress (Figure 9). However, there is an interaction effect of E_{sub} and the elastic modulus of the base course (E_{ctb}). The thickness of the stabilized base has a fairly linear reduction effect on the value STRC, and the rate of the reduction is dependent on the value E_{ctb} (Figure 4).

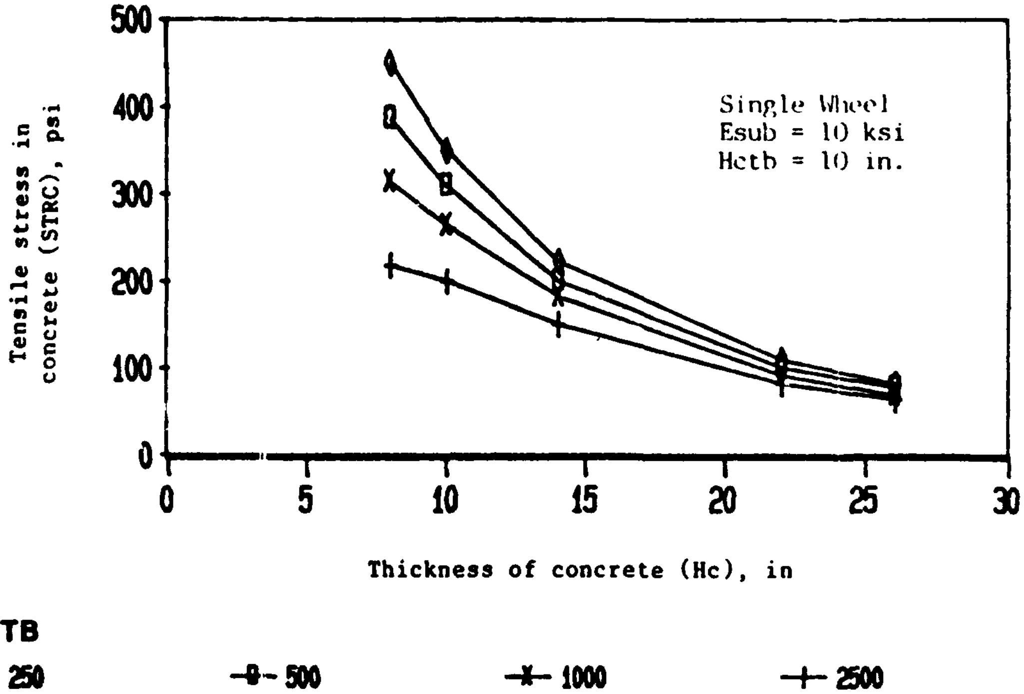


Figure 3. Relationship between concrete thickness and stress in the concrete slab for all CTB moduli

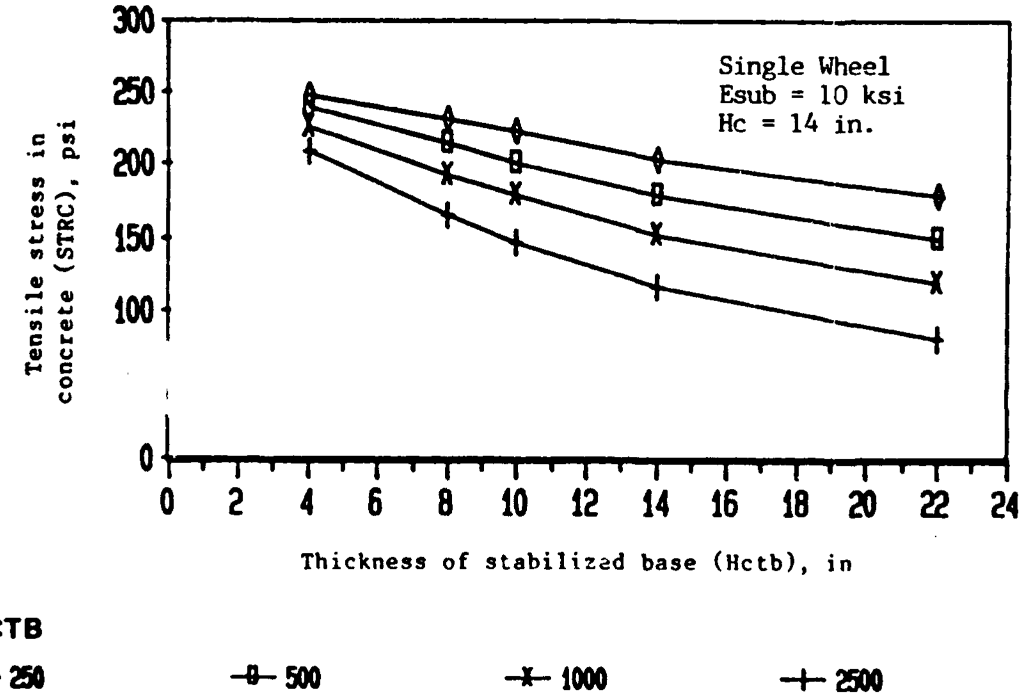


Figure 4. Relationship between CTB thickness and stress in the concrete slab for all CTB moduli

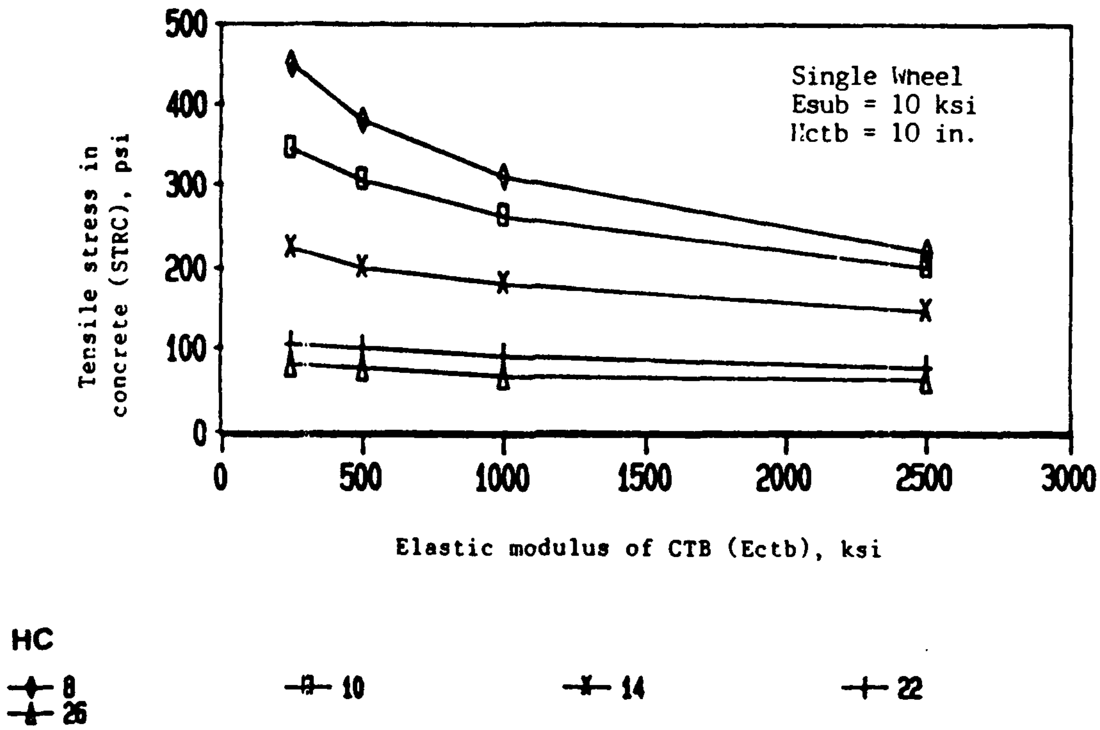


Figure 5. Relationship between CTB moduli and stress in the concrete slab for all concrete thicknesses

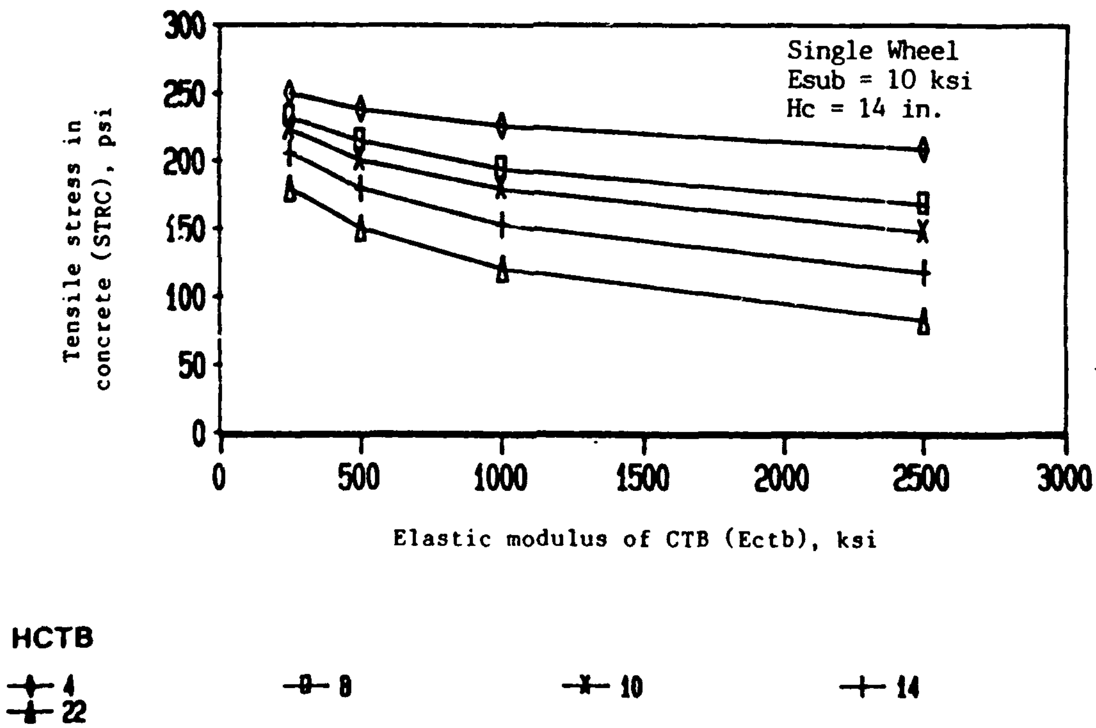


Figure 6. Relationship between CTB moduli and stress in the concrete slab for all CTB thicknesses

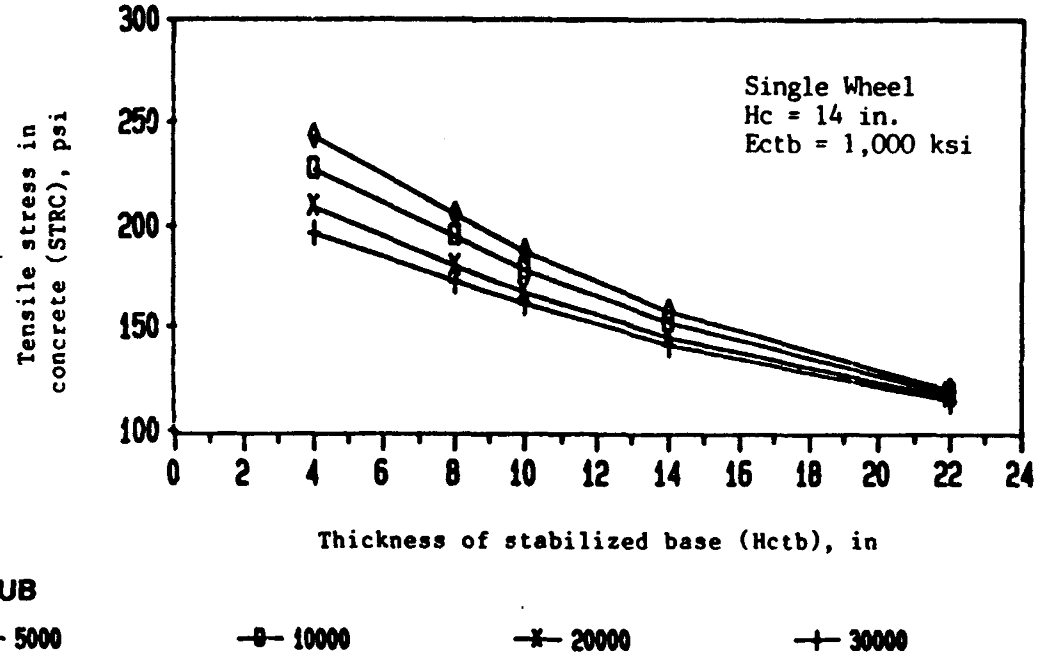


Figure 7. Relationship between CTB thicknesses and stress in the concrete slab for all subgrade moduli

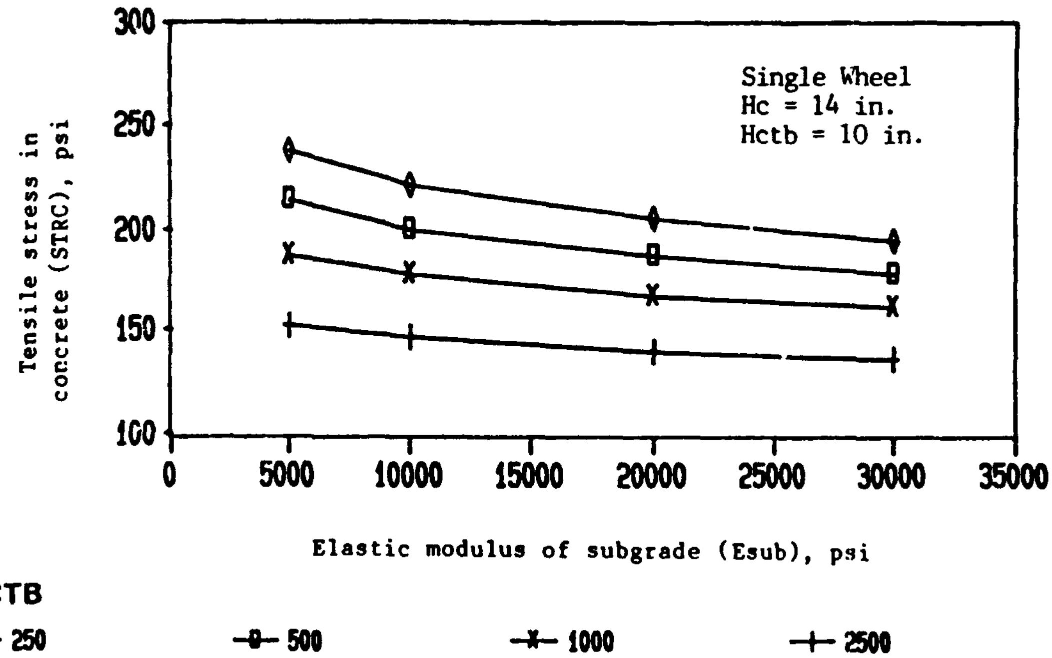


Figure 8. Relationship between subgrade moduli and stress in the concrete slab for all CTB moduli

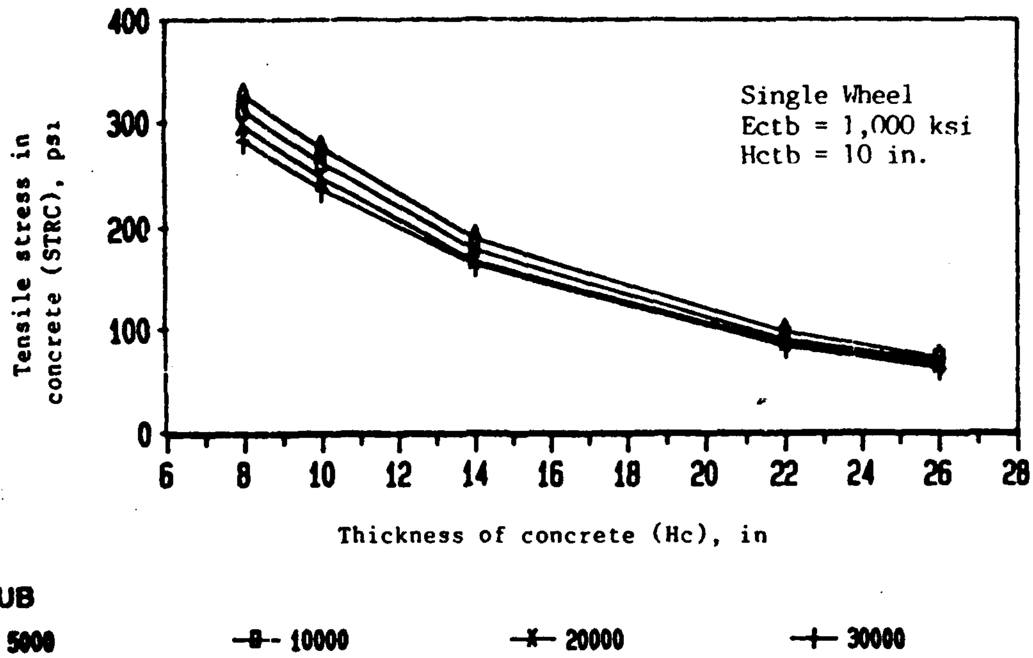


Figure 9. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli

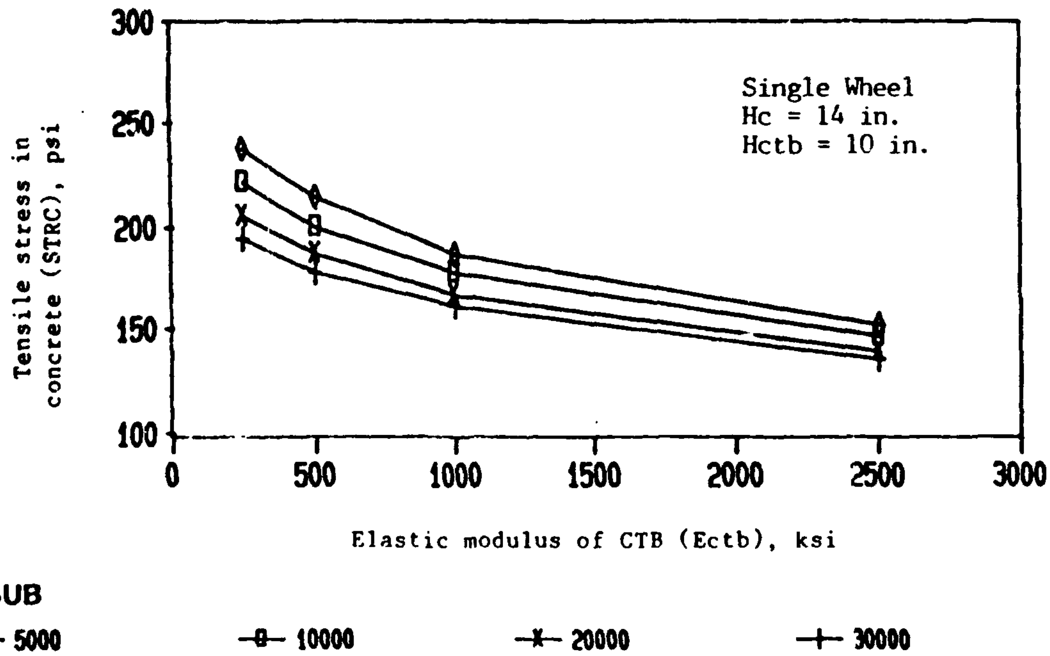


Figure 10. Relationship between CTB and stress in the concrete slab for all subgrade moduli

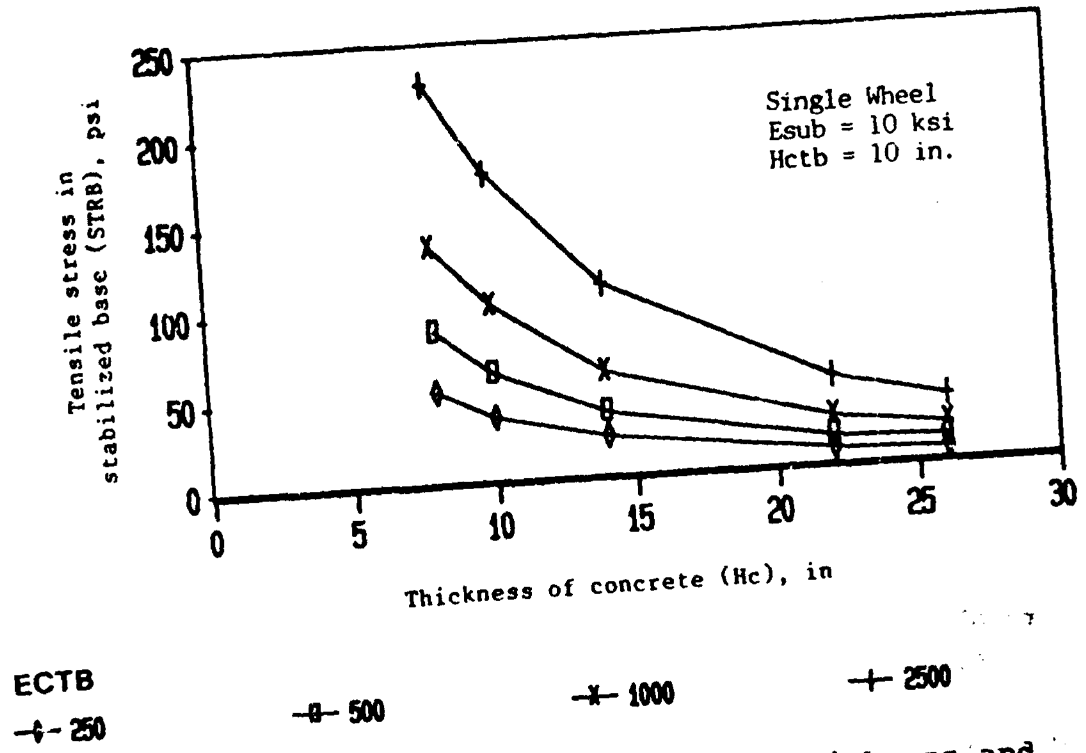


Figure 11. Relationship between concrete thickness and stress in the CTB for all CTB moduli

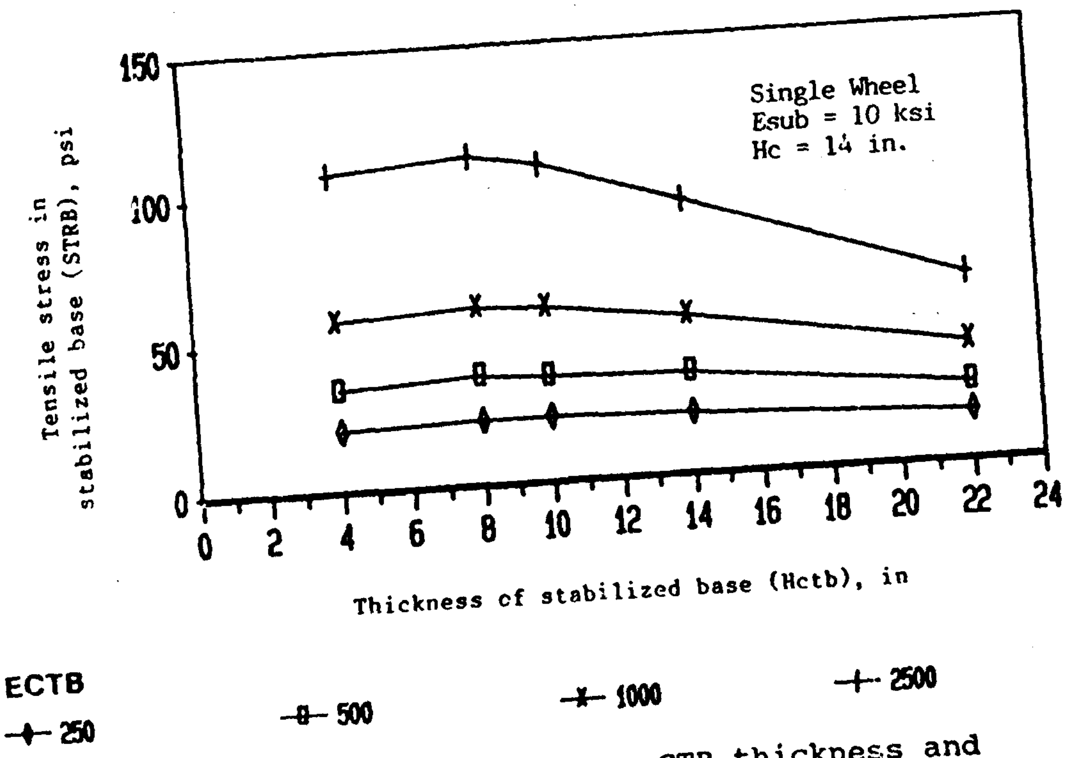


Figure 12. Relationship between CTB thickness and stress in the CTB for all CTB moduli

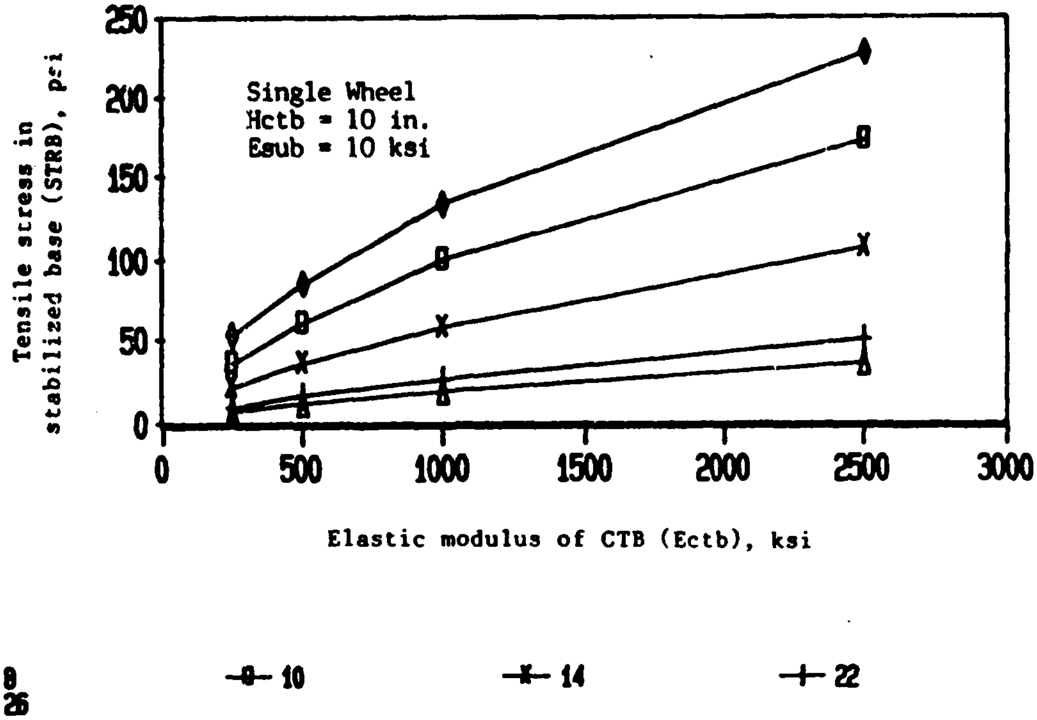


Figure 13. Relationship between CTB moduli and stress in the CTB for all concrete slab thicknesses

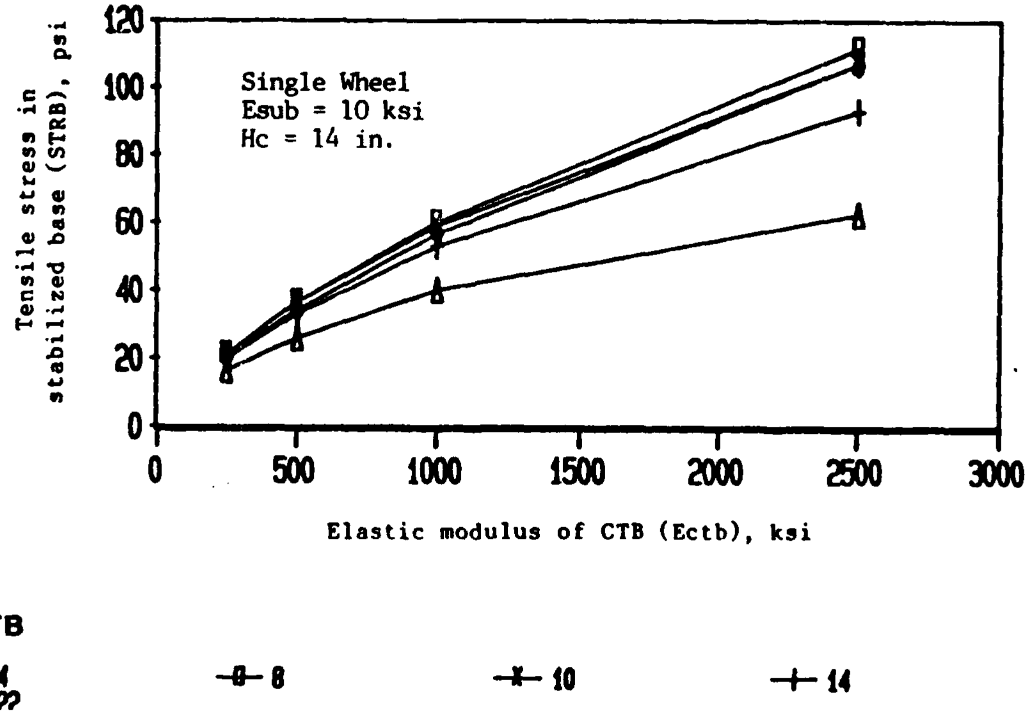


Figure 14. Relationship between CTB moduli and stress in the CTB for all CTB thicknesses

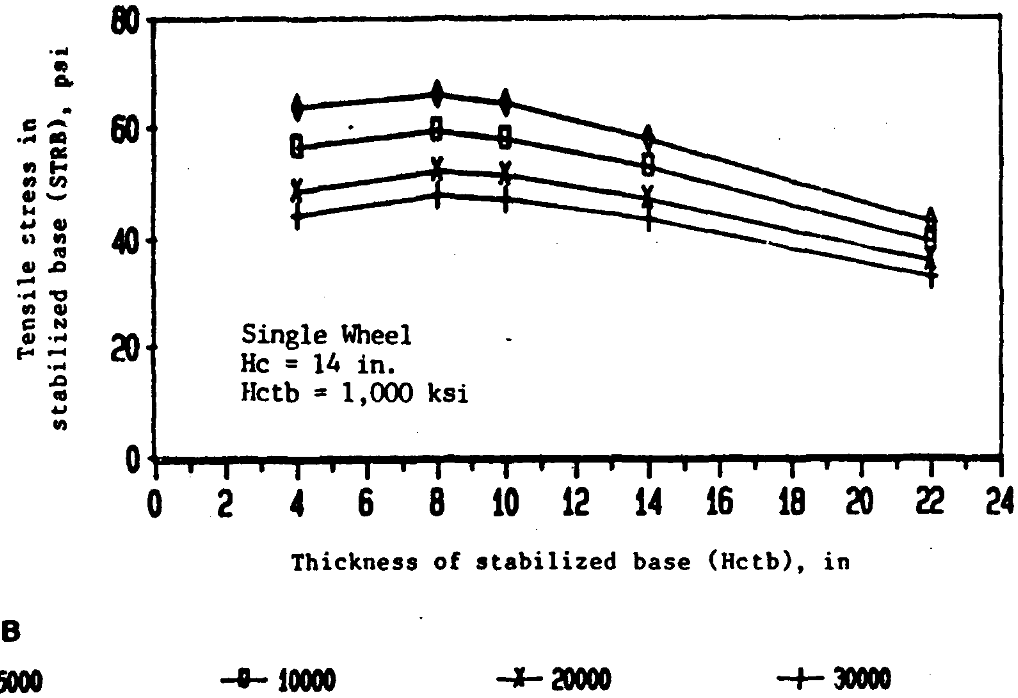


Figure 15. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

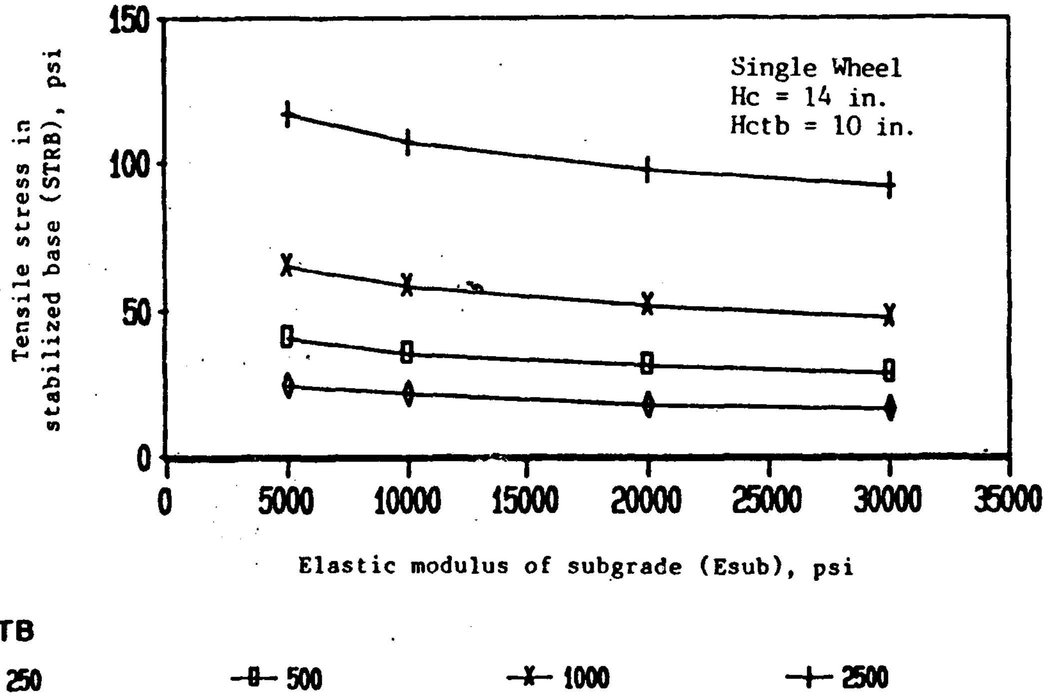


Figure 16. Relationship between subgrade moduli and stress in the CTB for all CTB moduli

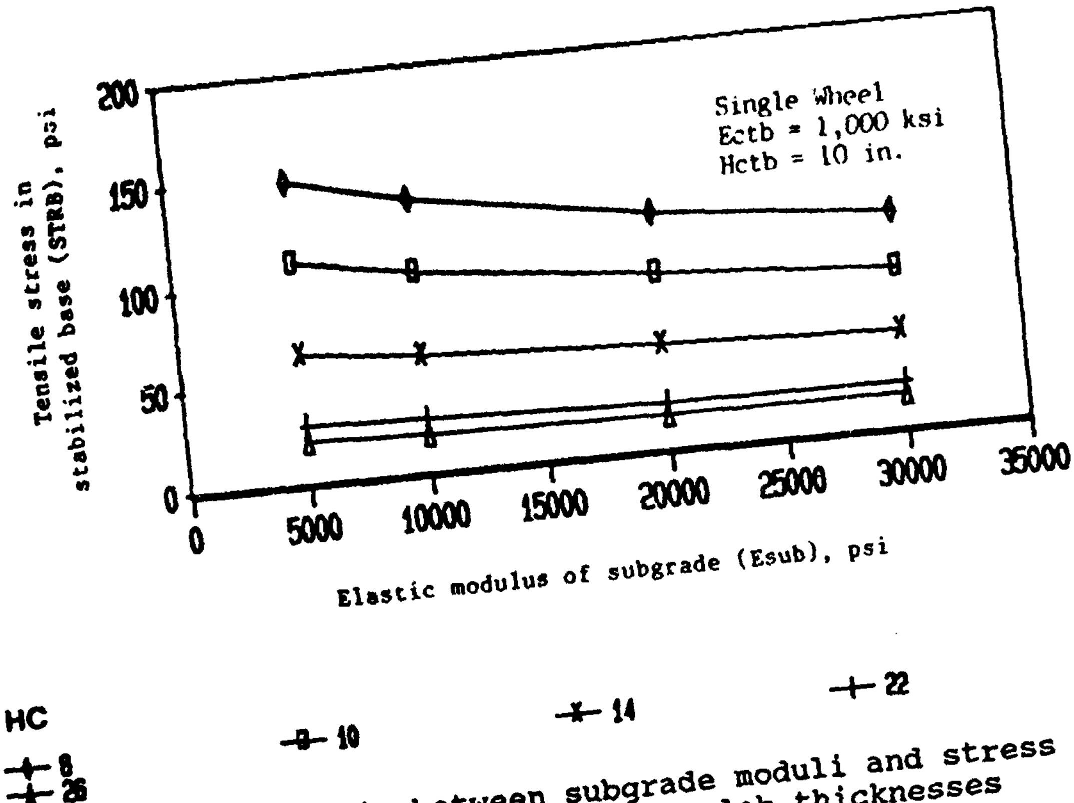


Figure 17. Relationship between subgrade moduli and stress in the CTB for all concrete slab thicknesses

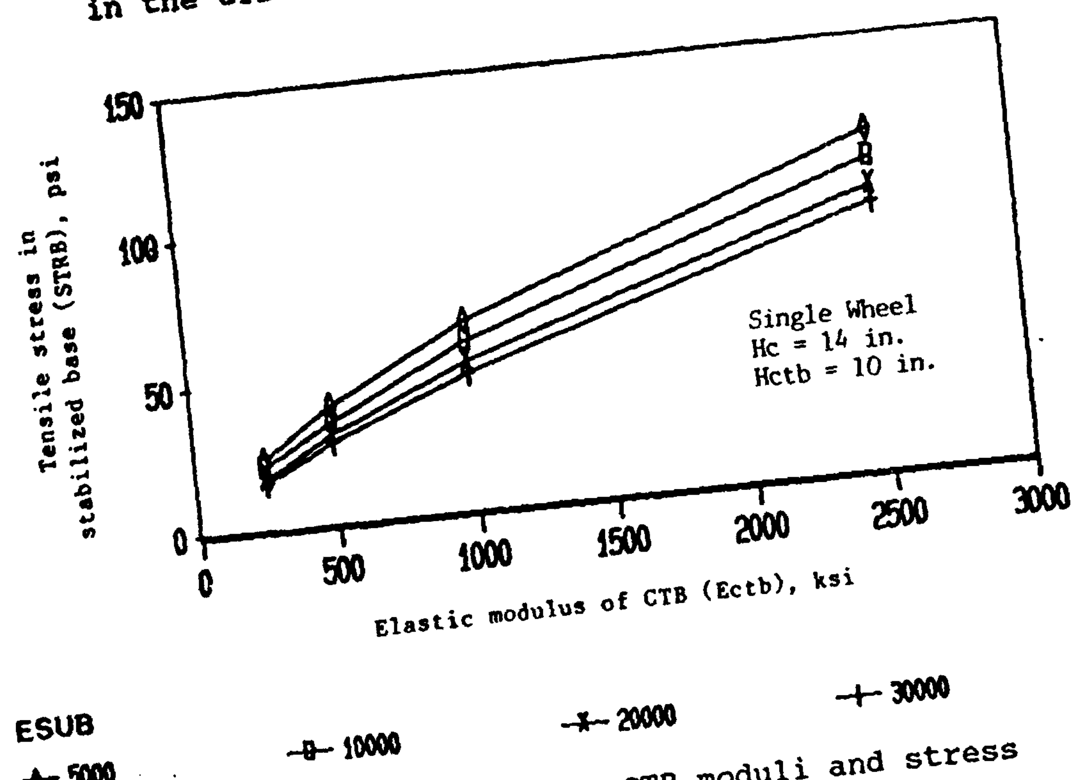


Figure 18. Relationship between CTB moduli and stress in the CTB for all subgrade moduli

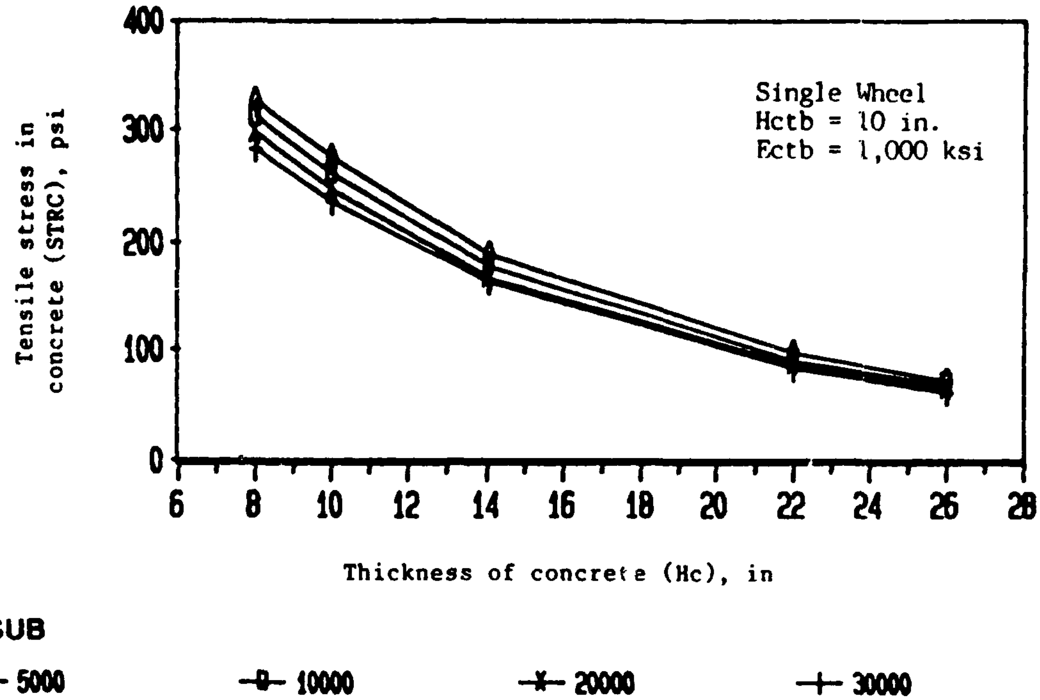


Figure 19. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli

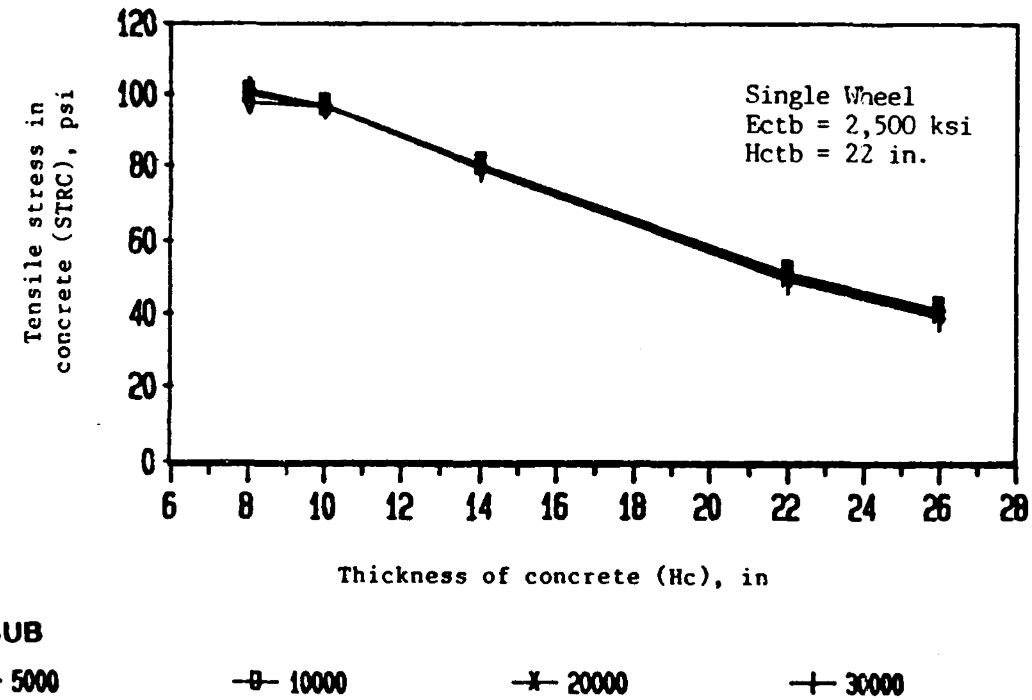


Figure 20. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli evaluated at the boundaries of the factorial

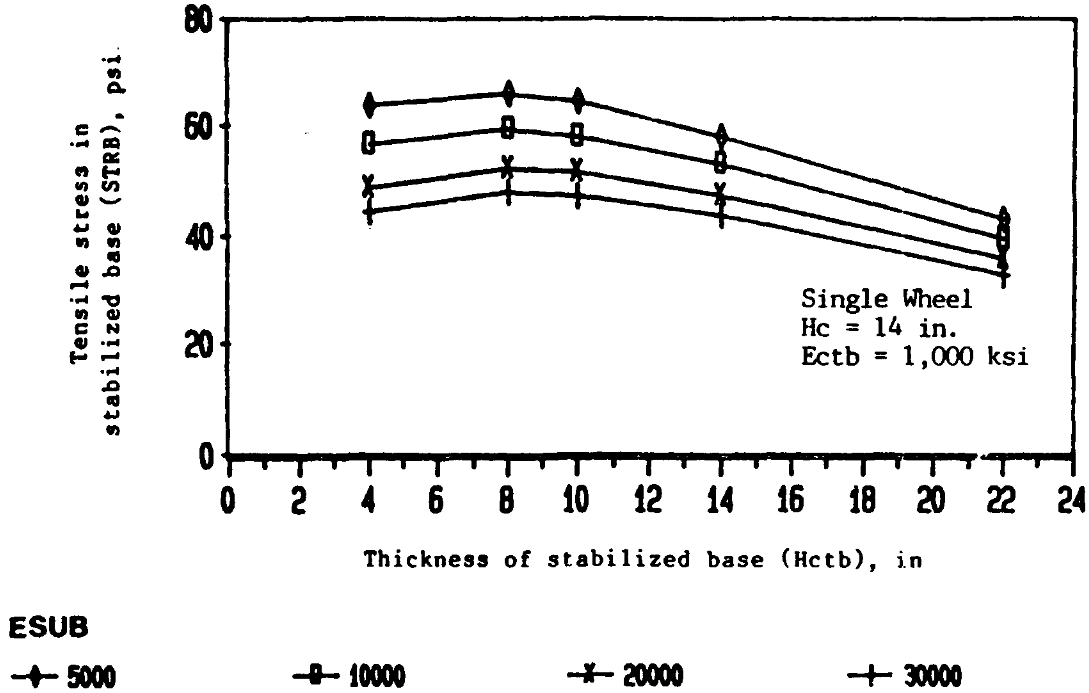


Figure 21. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

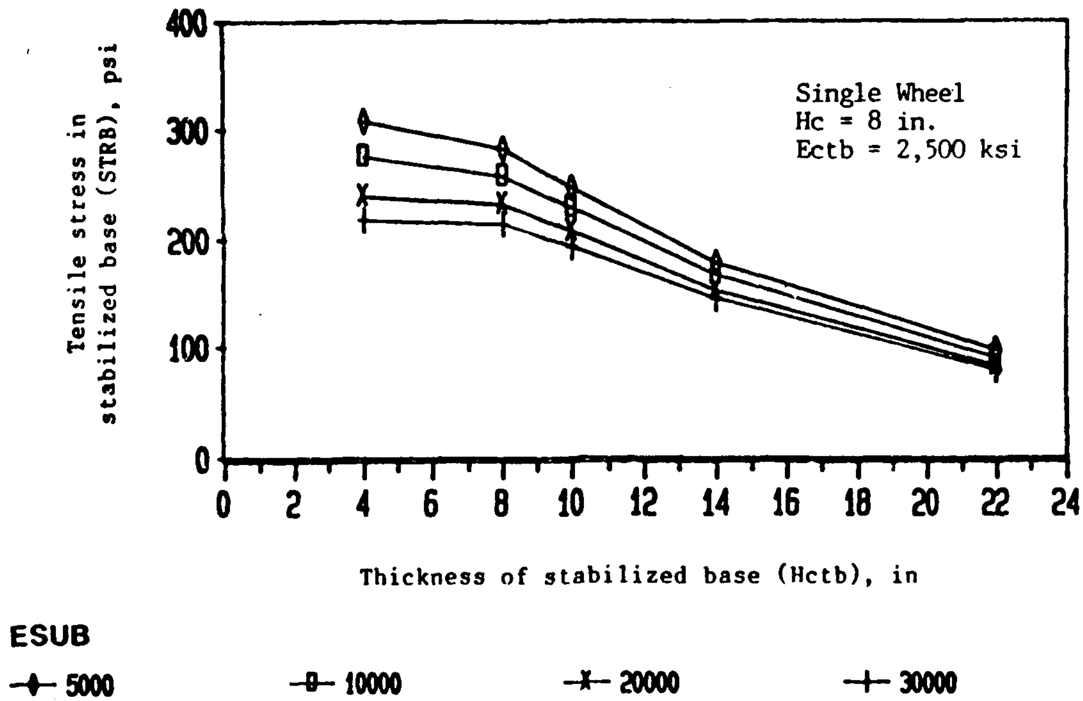


Figure 22. Relationship between CTB thickness and stress in the CTB for all subgrade moduli evaluated at the boundaries of the factorial

All these relationships are generally diminished as the slab thickness becomes very large (Figure 5). Thus, for a given load condition, the concrete slab thickness can overpower all parameters if it is extremely thick. This would happen in the case of over-designed pavements.

An interesting result is found when reviewing the graphs for the dual and dual tandem gears. It can be seen that the same general trends are produced for the multiple-wheel loads. This was somewhat expected since it was shown by Woinowsky-Krieger[12] that the tensile stress directly under the load plate could be estimated by an equation only involving the thickness of the slab and no other parameters. However, the effect of overlapping stresses from the multiple wheels was unknown prior to the analysis.

Stress in the Base Course

Figures 11 to 18 present the same primary relationships as Figures 3 to 10 for the stress in the STRB. In general, similar relationships hold. The thickness of the overlying slab has a large influence on the value of the STRB. The stress in the base as a function of the thickness of the base was found to be the most difficult relationship. As shown in Figures 12 and 17, this relationship tends toward a parabolic form. Thus, transformation to a linear function would be difficult. However, in the range of the factorial, this nonlinear behavior is not fully developed.

Unlike the value STRC, the stress in the base is not influenced greatly by the thickness of the base until better quality (higher E_{ctb}) materials are used. Figures 12 and 14 illustrate this behavior.

Again, the relationships for the dual and dual tandem gears were found to follow the same general trends. The slopes and magnitudes of the changes in stress are different but the shapes do remain fairly constant.

Boundary Relationships

The previous set of figures were developed for the mean pavement parameters. However, before pursuing any analysis procedures, conditions representing the boundaries of the factorial were developed. These relationships are presented in Figures 19 to 22. These graphs represent the relationships between the major variables and the stresses for the conditions at the four corners of the factorial. As shown, the relationships hold in a general sense, but it is shown (Figure 20) that interaction effects are present. That is relationships which were once approximately parallel over the range of thicknesses begin to cross and become non-

parallel. Also, the nonlinear behavior of the STRB value becomes magnified at the edges of the factorial.

Summary

These graphics present the general relationship between the stress values (STRC and STRB) and the materials and slab characteristics governing the design problem. The review of these graphs lead to the possibility that a single form could be used for determining the stress values for any gear configuration (the equation was modified by a gear factor). This can be expressed in the following form:

$$\text{Stress} = f(G) * f(h, E_{sub}, E_{ctb})$$

where $f(G)$ = gear factor

$f(h, E_{sub}, E_{ctb})$ = general function in terms of materials properties.

The other conclusion was that the determination of the stress in the base would be a more complex function since the parameter exhibited the parabolic nature especially at the extremities of the factorial.

At this point in the project it was determined that the two primary methods to consider were an analytical or a statistical approach. Graphic procedures were put aside at this point due to the complex interactive effects of the variables.

STRESS DETERMINATION PROCEDURES

Introduction

The objective is to design a two-layer rigid (surface and base) pavement system that will provide equivalent performance to a one-rigid layer (surface) pavement system as determined by the current FAA procedures. The new design method is based on obtaining equal maximum tensile stress at the bottom of the concrete layer in a two-layer pavement system without exceeding the allowable tensile stress levels in the rigid base.

This section describes the methods investigated and the method selected to predict the maximum tensile stress in each of the pavement layers.

Methodology

Initially, two theoretical approaches were investigated in order to predict the required pavement behavior. The two approaches were both an equivalent thickness approach. One method relied on an equal rigidity concept and the other was based on an equivalent stress concept. These methods are used frequently in overlay design to determine the thickness of the overlay slab. In many respects the design of a two rigid layer system is very similar to overlay design. It was thought that modification of the equivalent thickness for gear load and subgrade effects could be developed to provide a system of equal stress and therefore equal performance. The equation used in this analysis is as follows:

$$H_e = (H_s^n + H_{ctb}^n) * F(Eb) \qquad (1)$$

where

H_e = the equivalent thickness

H_s = the surface thickness

H_{ctb} = the base thickness

n = a power determined by the method used

$F(Eb)$ = a modular ratio term.

This equation can be developed from simple beam theory as presented by Kohn and Rollings [3]. Once the equivalent thickness was determined, the equivalent pavement system were treated as a linear elastic slab supported by a dense liquid. Westergaard's stress equation is then used to determined the required pavement behavior.

Neither approach was successful in predicting the maximum tensile stress at the bottom of the concrete slab as determined by the elastic theory. The major problem in developing the necessary modifying functions was the interaction effects at the boundary of factorial. Thus, the linear regression analysis was selected to predict the tensile stress with an acceptable level of accuracy.

Regression Analysis

Five factors were evaluated in this study to investigate their influence on the maximum tensile stress at the bottom of the concrete layer. The maximum tensile stress has been clearly identified as having a great influence on the structural performance of rigid pavement systems. The five variables are:

a. Loading or gear type, GT

b. Modulus of elasticity of the CTB, E_{ctb}

c. Thickness of the concrete surface, H_{conc}

d. Thickness of the CTB, H_{ctb}

e. Elastic modulus of the subgrade, E_{sub}

The linear regression analysis was performed using the Statistical Package for Social Studies (SPSS) microcomputer program. SPSS is a widely accepted program used in both the social science and engineering fields for statistical analysis. The program offers a wide range of regression methods, and allows for building transformation variables. The steps involved in the selection of the final form of the equation were as follows:

a. Identification of a large set of variables which are thought to influence the stress state of the pavement system.

b. Selection of the variables which are thought to have the most influence on the pavement response. Three factors controlled the selection variables:

   (1). variables should be a function of pavement geometry and/or material properties.

   (2). the form of the equation should be the same for all gear types.

(3). the resulting equation should provide the least variability from the stresses generated in the factorial design for each gear type.

c. Once the equation is developed, a statistical model and adequacy check is performed. If the model is statistically inadequate, return to step b.

Selection of Variables

Based on the figures shown in the previous section, it was obvious that strong interactions exist between the factors considered in this study. The need to consider interactions between the factors was also identified by obvious patterns in early stage residual plots and by strong intercorrelation between the factors in the correlation matrix when only the main effects were considered. The figures also illustrated that power and log functions represent most relationships between the different factors.

Based on these observations, a large set (over 100 initially) of variables consisting of interactions between the factors investigated and other related variables created. Trial and error procedures were used to select the appropriate power functions. Factors that were observed in the equivalent thickness approach were also used to develop variables.

Westergaard's stress solution for an interior load on a slab supported by a dense liquid indicated that the radius of relative stiffness of the slab is a very important parameter. The radius of relative stiffness is the inverse of the parameter lambda determined from the displacement equation of a beam on a Winkler foundation. The unit of the radius of relative stiffness is length. It is a measure of the interaction effect between the slab and the subgrade. If the distance is large the deflection of the soil and beam will be over a large area, whereas if the distance is small the influence of the load will be localized. In the case of the three layer system the value of the radius of relative stiffness calculated using the properties of the surface and the subgrade is not sufficient to determine the stress in both layers.

An attempt was made to develop an equivalent radius of relative stiffness for the two rigid layers using the equivalent thicknesses described earlier. However, this attempt was unsuccessful since it did not account for the

variability observed in the pavement response (STRC). A radius of relative stiffness was determined for the surface (L_1) and base (L_2) slabs assuming they are supported by the same dense liquid. Interactions between L_1 and L_2 or between functions of L_1, L_2 and/or other variables accounted for most variability in STRC.

The equivalent slab thickness, based on equal tensile stress at the bottom of the slab, indicated that the ratio of the modulus of the different layers is an important variable. Consequently, these ratios were considered in the analysis.

The second step in the variable selection process involved using the stepwise variable elimination procedure provided by SPSS. This procedure reduced the number of variables to a manageable number without greatly affecting the accuracy in predicting STRC.

The third step was to check the adequacy of the model to ensure the selection of a sound statistical model. This part of the process is required to eliminate gross errors in the prediction of the stress. Normal probability plots and residual plots were used to complete this part of the process.

The main components of the variables that entered the equations are listed below:

Er_1 = ratio of concrete modulus to the CTB modulus

Er_2 = ratio of CTB modulus to elastic modulus of the subgrade

H_c and H_{ctb} = thickness of concrete slab and stabilized base, respectively

L = radius of relative stiffness of the concrete slab for the one rigid layer pavement system

L_1, L_2 = radius of relative stiffness of the concrete slab and stabilized base, respectively, for the two rigid layer pavements systems

K = modulus of subgrade reaction

E_{sub} = Elastic modulus of the subgrade

Results of the One-Rigid Layer System

The maximum tensile stress in the concrete slab was predicted for this case. One equation form was developed for all three gear configurations. Naturally, different regression coefficients were computed for each gear type. The general form of the equation is as follows:

$$SC = P/P1\ \{CONSTANT + a1*\ln(E_{sub}) + 1/H_{conc}^{2}*[a3*L + a4*K] + \ln(L)*[a5*H_{conc} + a2*\ln(E_{sub})] + a6*1/H_{conc}^{3}\} \qquad (2)$$

where

$$L = \{\ [E_{conc} * H_{conc}^{3}]\ /\ [12\ (1 - u^{2}) * K]\ \}^{0.25}$$

$$\log K = (\log E_{sub} - 1.415)\ /\ 1.284$$

ai = regression coefficients

SC = maximum tensile stress slab-on-grade

Er = Modulus ratio

H_{conc} = concrete thickness

L = radius of relative stiffness

K = modulus of subgrade reaction

P = design gross aircraft load

P1 = 84,000 lb for single wheel aircraft
190,000 lb for dual wheel aircraft
305,000 lb for dual tandem aircraft

The values of the regression coefficients ai, the correlation coefficients R^2, and the standard error for each gear type are given in Table 1. The regression equations provided excellent predictions for the maximum tensile stress as seen in the values of R^2 and standard error. A standard error of 2.7 psi was computed which represents 0.63 percent of the mean stress value for the dual-wheel gear. The maximum standard error calculated was equal to 0.75 percent and corresponded to the single wheel gear type. Plots illustrating the agreement between predicted and computed stress values are shown in Figure 23 through 25 for

the single wheel, dual wheel, and tandem gear types, respectively. Additional plots illustrating variance in the residuals of the selected models are shown in Figures 26 through 28.

Table 1

Regression Coefficients, Interior Stress for Slab-On-Grade

REGRESSION COEFFICIENTS	GEAR TYPE SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	79.87059	70.87699	-104.54994
a2	-20.83124	-13.20461	41.08126
a3	1043.40315	1886.23113	1754.38235
a4	-28.99054	-35.41080	31.44690
a5	1.11244	0.91015	-1.86926
a6	33382.69811		-74244.45618
Constant	-54.80360	-307.15867	-601.92659
R2	0.99988	0.99991	0.99987
Standard Error, psi	2.08718	2.70057	2.09560
Standard Error, % error	0.75	0.63	0.67

It is important to note that no strong patterns were observed in the residual plots. This indicates that the selected model is adequate to predict the tensile stress in the concrete slab when the design inputs are within the valid range of the investigated factors. As indicated earlier in this report, the range of design inputs was selected to include most practical pavement design applications.

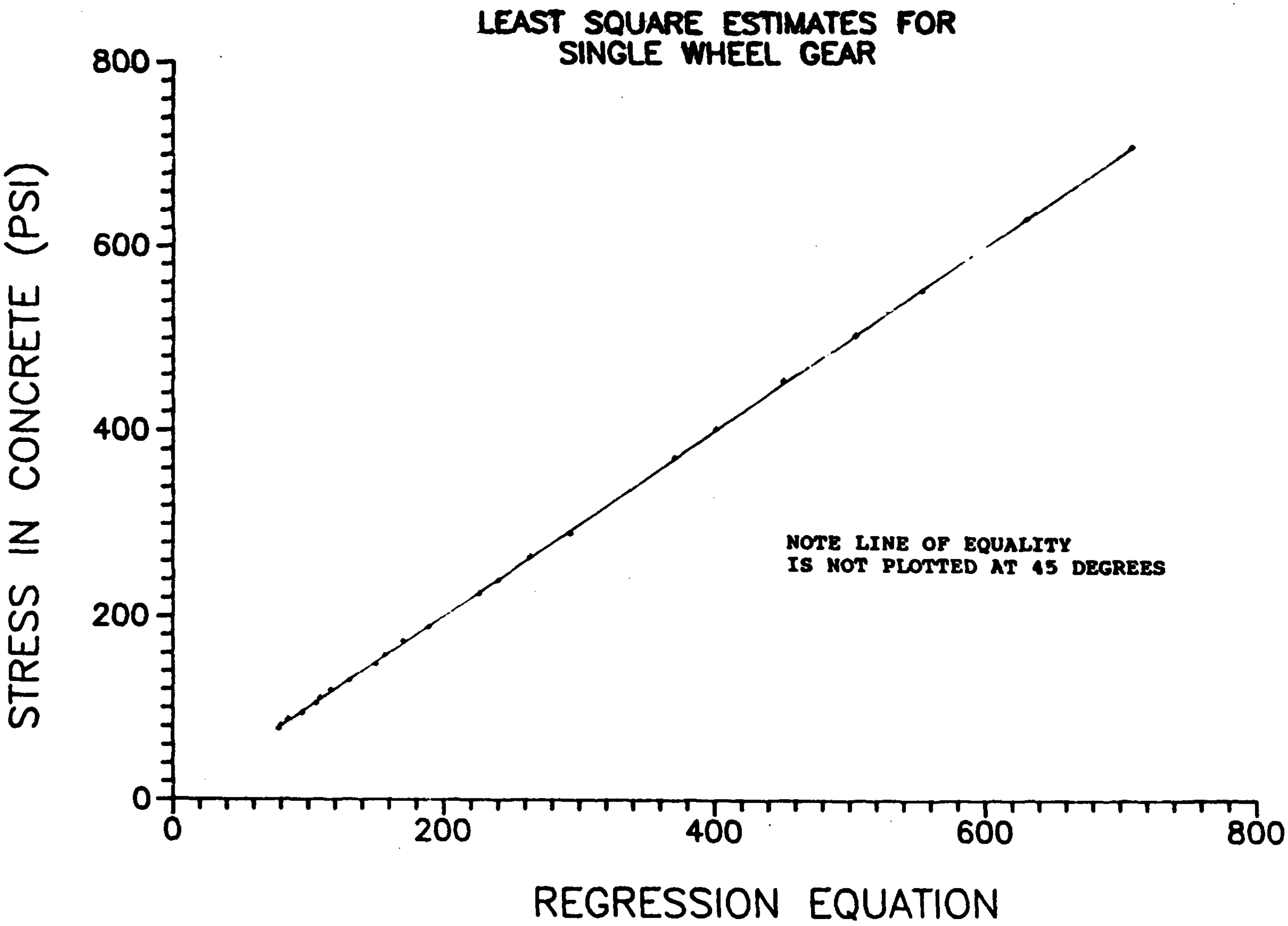


Figure 23. Comparison of predicted versus actual stress values for the case of a single-wheel gear and the slab-on-grade condition

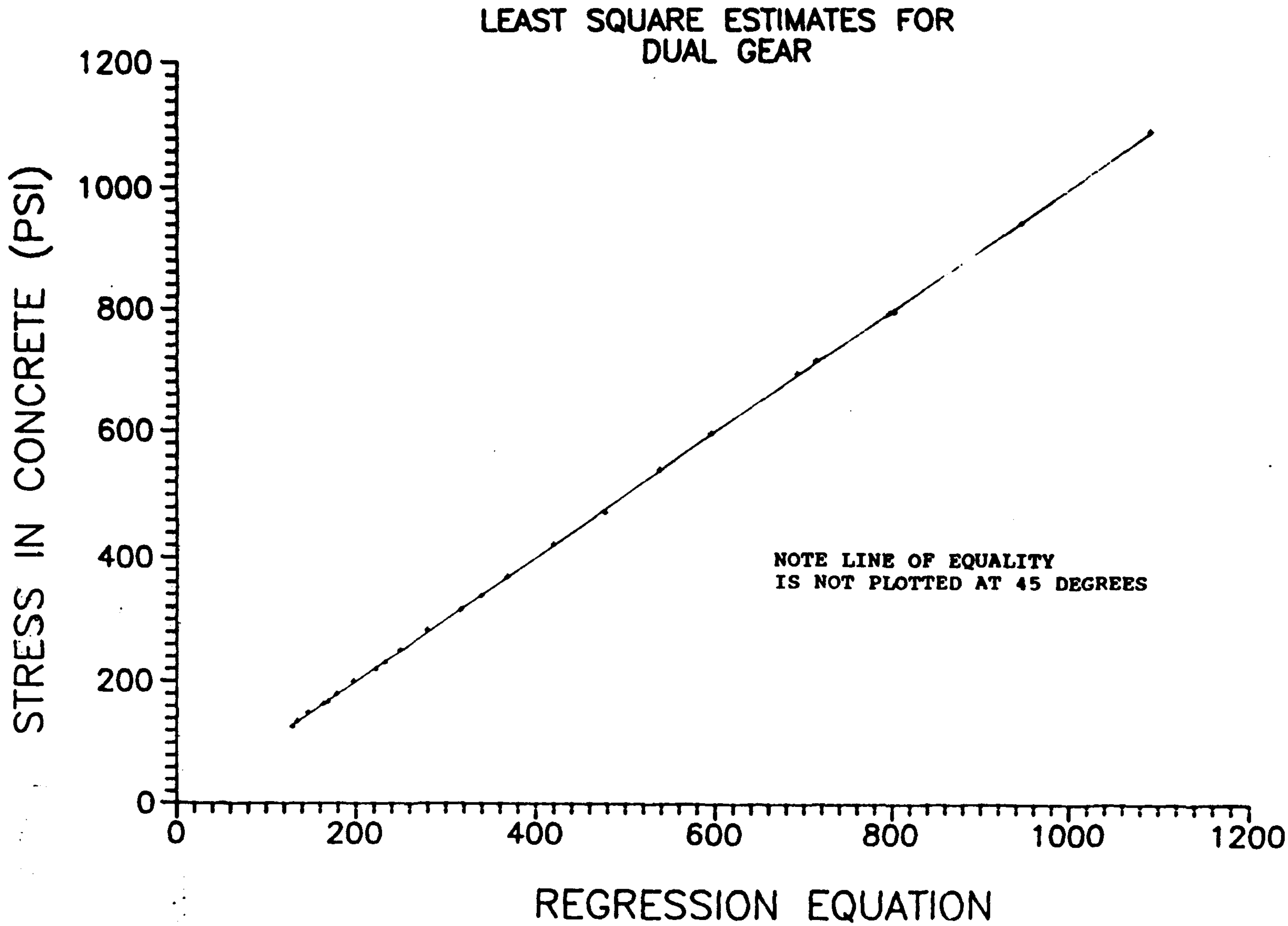


Figure 24. Comparison of predicted versus actual stress values for the case of a dual-wheel gear and the slab-on-grade condition

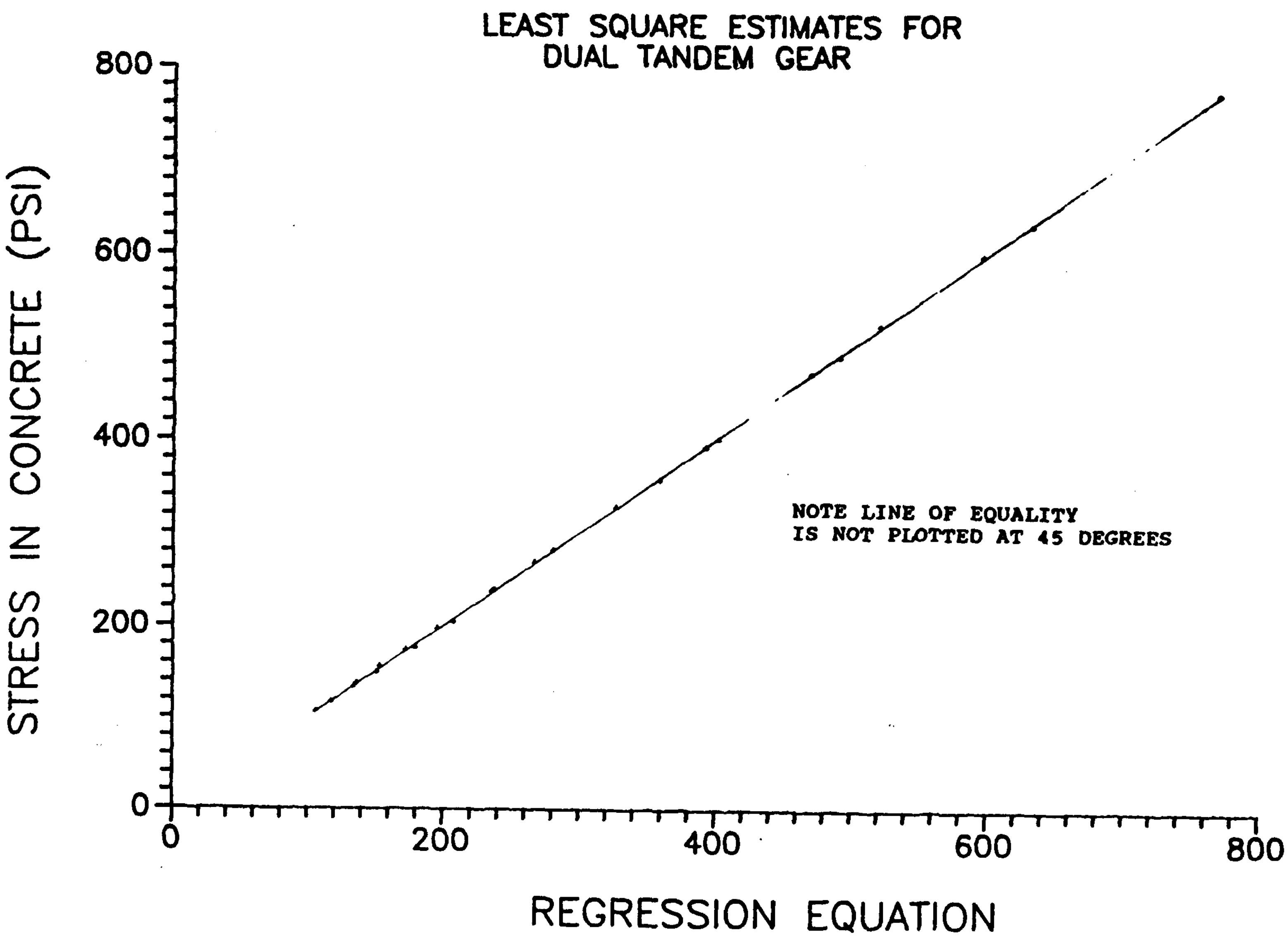


Figure 25, Comparison of predicted versus actual stress values for the case of a dual-tandem gear and the slab-on-grade condition

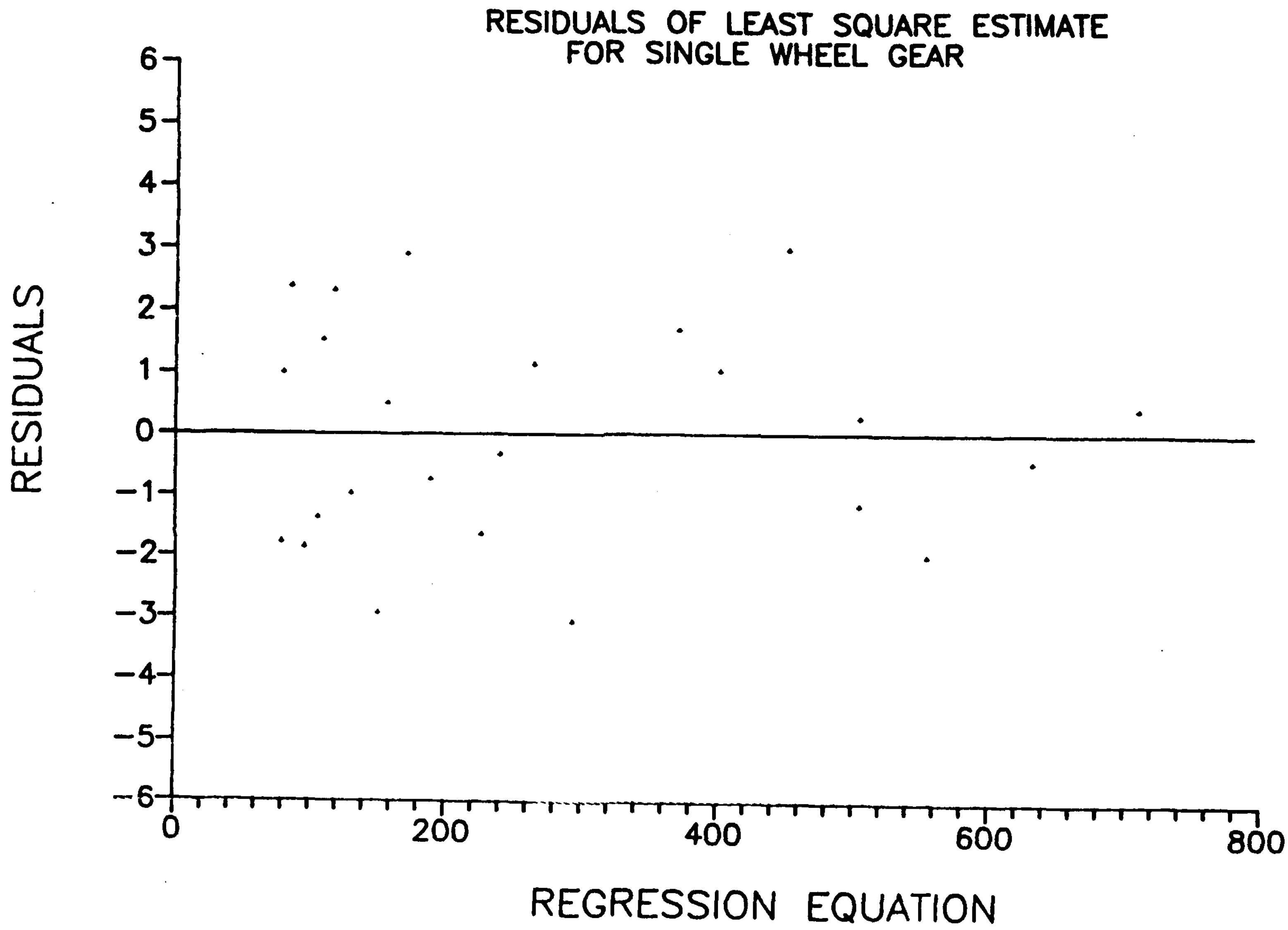


Figure 26. Residual plot obtained from the statistical model selected for the single-wheel gear (slab-on-grade condition)

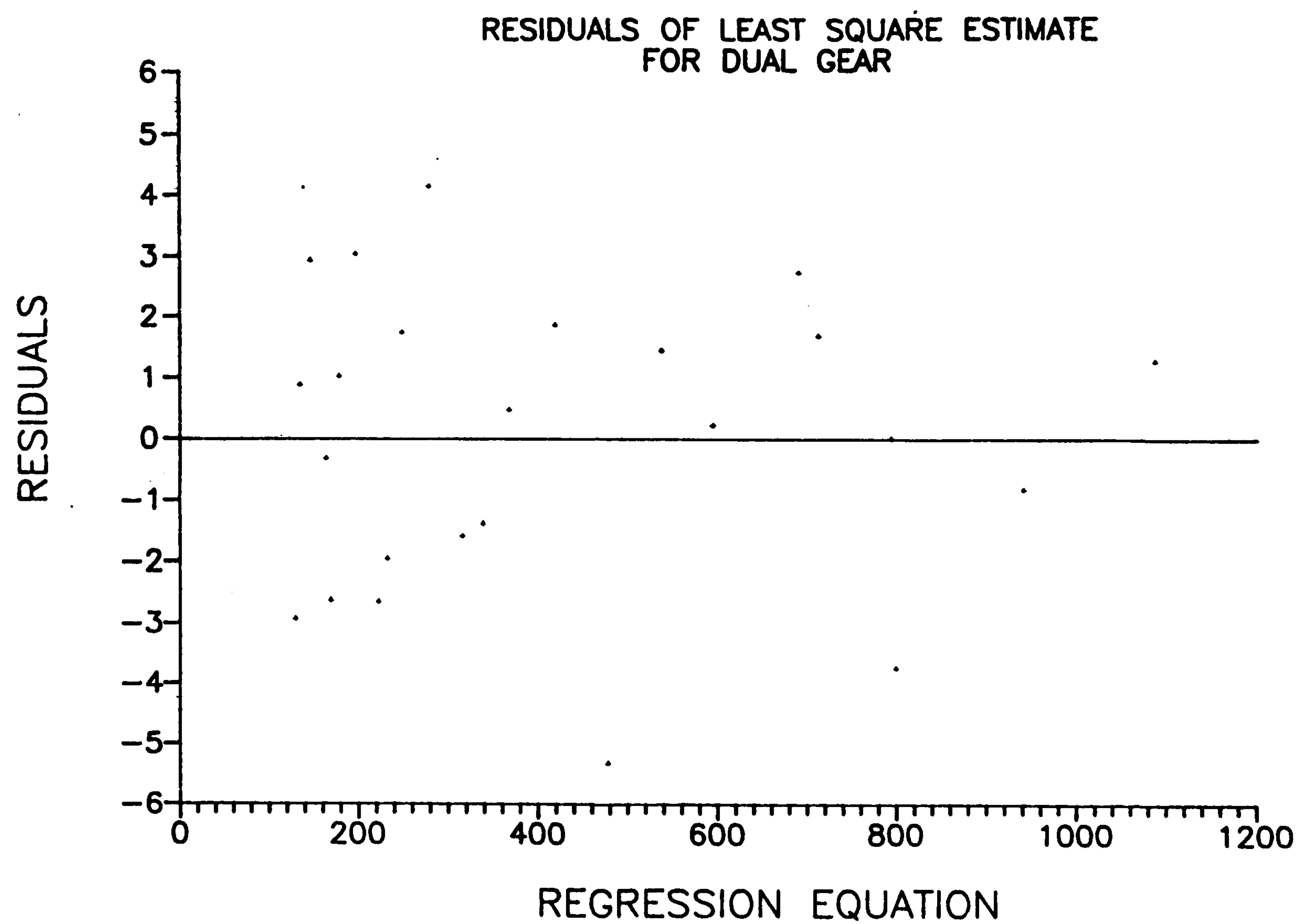


Figure 27. Residual plot obtained from the statistical model selected for the dual-wheel gear (slab-on-grade condition)

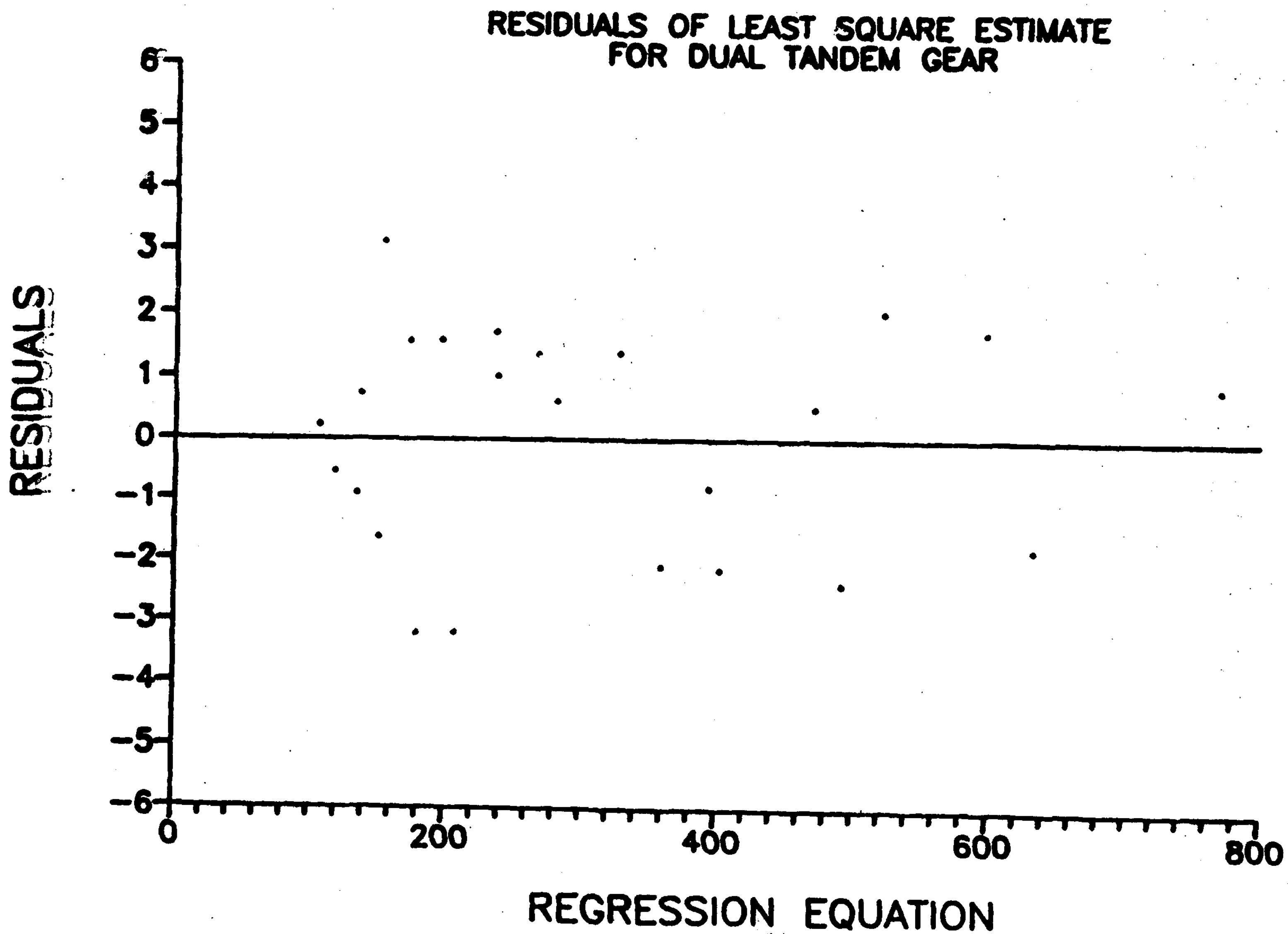


Figure 28. Residual plot obtained from the statistical model selected for the dual-tandem gear (slab-on-grade condition)

Results of the Two-Rigid Layer Pavement System

For this case, the maximum tensile stress in the concrete slab and the cement-treated base were predicted. The equation was selected to provide the best fit using one equation form for all gear types.

The equation for the STRC is as follows:

$$STRC = P/P_1(CONSTANT + a1\ \ln(L_1)/L_1 + H_{conc}*\ln(L_1)\ \{ a2 + a5 * L_2] + 1/H_{conc}^{2} * \{ a3* L_1 + a6* Er_1*L_1 + a9* L_2 + a_{11}* K*(L_1/L_2) + a8* L_2*L_1 \} + B * \{ a4 + a7* Er_2 + a_{10}* L_2 + a_{12}* (Er_1/E_{sub})^{0.25} \}) \qquad (3)$$

<u>where</u>

ai = regression coefficients (see Table 2)

Er_1 = E_{conc} / E_{ctb} ; $Er_2 = E_{ctb} / E_{sub}$

L_1 = $\{ [E_{conc} * H_{conc}^3] / [12\ (1 - u^2) * K] \}^{0.25}$

L_2 = $\{ [E_{ctb} * H_{ctb}^3] / 12\ (1 - u^2)*K] \}^{0.25}$

log K = $(\log E_{sub} - 1.415) / 1.284]$

B = $1/H_{conc}^{0.33} * \ln(L_1/H_{conc})*(H_{ctb}/H_{conc})^2*(Er_1)^{-.25}$

STRC = maximum tensile stress in the concrete

H_{conc} = concrete thickness

H_{ctb} = cement treated

L = radius of relative stiffness

K = modulus of subgrade reaction

P = design gross aircraft load

P_1 = 84,000 lb for single wheel aircraft
190,000 lb for dual wheel aircraft
305,000 lb for dual tandem aircraft

The values of the regression coefficients along with other statistical parameters are presented in Table 2. Relatively good correlation was obtained for all gear types considering the complexity of the three layer pavement system. Minor changes in any of the parameters representing the different pavement layers causes significant changes in the observed pavement response. The maximum standard error computed for the regression equations was equal to 2.55 percent of the mean tensile stress. This value corresponds to the dual-tandem gear.

Table 2

Regression Coefficients, Interior Stress in the Concrete Slab for the Two-Rigid Layer System

REGRESSION COEFFICIENTS	GEAR TYPE		
	SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	3152.60047	3903.81004	5463.62830
a2	0.74036	1.06777	
a3	1206.42011	1839.96268	1304.04836
a4	40.117044	79.37649	66.63757
a5	2.891281E-03		
a6	3.8000969811	6.99535	5.63003
a7	0.02337	0.03171	0.03013
a8			-5.30015
a9	-925.25867	-1421.66496	-820.59149
a10	0.45975	0.73535	0.36554
a11	-5.58656	-10.42594	-7.26875
a12	-44.92398	-195.49499	-139.49406
Constant	-307.75101	-388.66280	-41.35524
R2	0.99912	0.99905	0.99814
Standard Error, psi	3.66431	5.55339	5.26719
Standard Error, % error	1.96	1.98	2.55

The high degree of variability associated with this gear type can be justified by considering the following factors. The predicted pavement response is the maximum tensile stress in the concrete slab and not the tensile stress at one location within the pavement system. As the thicknesses and material properties changed in the factorial design, the location of the maximum tensile stress within each of the rigid layers also changed. It is believed that this variation in the maximum tensile stress location accounts for most of the variability observed in the

regression results. The same phenomenon was also observed, but to a lesser degree in the dual wheel results. The magnitude of the variance caused by this phenomenon is much greater for the stress in the base.

The largest magnitude of the standard error observed for all gear types is equal to 5.55 psi which is acceptable for all practical design applications.

Figures 29 through 31 show the agreement between the predicted and computed stress values for all three gear types. Figures 32 through 34 present the residuals for each of the three equations. These residuals do not show any gross violations for the assumptions (i.e. normality and equal variance of the error term) made during the statistical analysis.

The stress in the cement-treated base course was also predicted. For this value the natural log of the maximum tensile stress in the base was predicted. The logarithmic transformation was required to reduce the variance in the error term which, otherwise, would have violated one of the basic assumptions of statistical analysis. This high magnitude of the variance can be explained in part by the change in the maximum tensile stress which was addressed in the previous paragraphs and the nonlinear behavior of the function at the extremities of the factorial.

The selected model fits all gear types with an acceptable level of accuracy. The regression equation developed is as follows:

$$\begin{aligned}Ln(STRB) = {} & CONSTANT + (Er_1/E_{sub})^{0.25}\{a5\ H_{conc}*ln(L_1) + a6 * \\ & Er_2 + a10 * Er_1 + a12\} + K/H_{conc}^2\ \{a1\ H_{ctb}^2 + a4 \\ & L_1/L_2\} + Ln(L_1)*\ H_{conc}\{a3\ L_1/H_{conc}^2 + a7\ B + a11 \\ & Ln(L_1)/L_1\} + Er_1 * \{a2 + a8\ L_2\} + a9\ Ln(L_1)/L_1 \qquad (4)\end{aligned}$$

$$STRB = P/P_1(\exp(Ln(STRB))) \qquad (5)$$

<u>where</u>

$Er_1 = E_{conc} / E_{ctb}$

$Er_2 = E_{ctb} / E_{sub}$

$$L_1 = \{ [E_{conc} * H_{conc}^3] / [12 (1 - u^2) * k] \}^{0.25}$$

$$L_2 = \{ [E_{ctb} * H_{ctb}^3] / [12 (1-u^2) * k] \}^{0.25}$$

$$\log k = (\log E_{sub} - 1.415) / 1.284$$

$$B = 1/H_{conc}^{0.33} * \ln(L_1/H_{conc}) * (H_{ctb}/H_{conc})^2 * (Er_1)^{-.25}$$

ai = regression coefficients (see Table 3)

STRB = maximum tensile stress in the CTB

H_{conc} = concrete thickness

H_{ctb} = cement-treated base thickness

L = radius of relative stiffness

k = modulus of subgrade reaction

P = design gross aircraft load

P_1= 84,000 lb for single-wheel aircraft
190,000 lb for dual-wheel aircraft
305,000 lb for dual-tandem aircraft

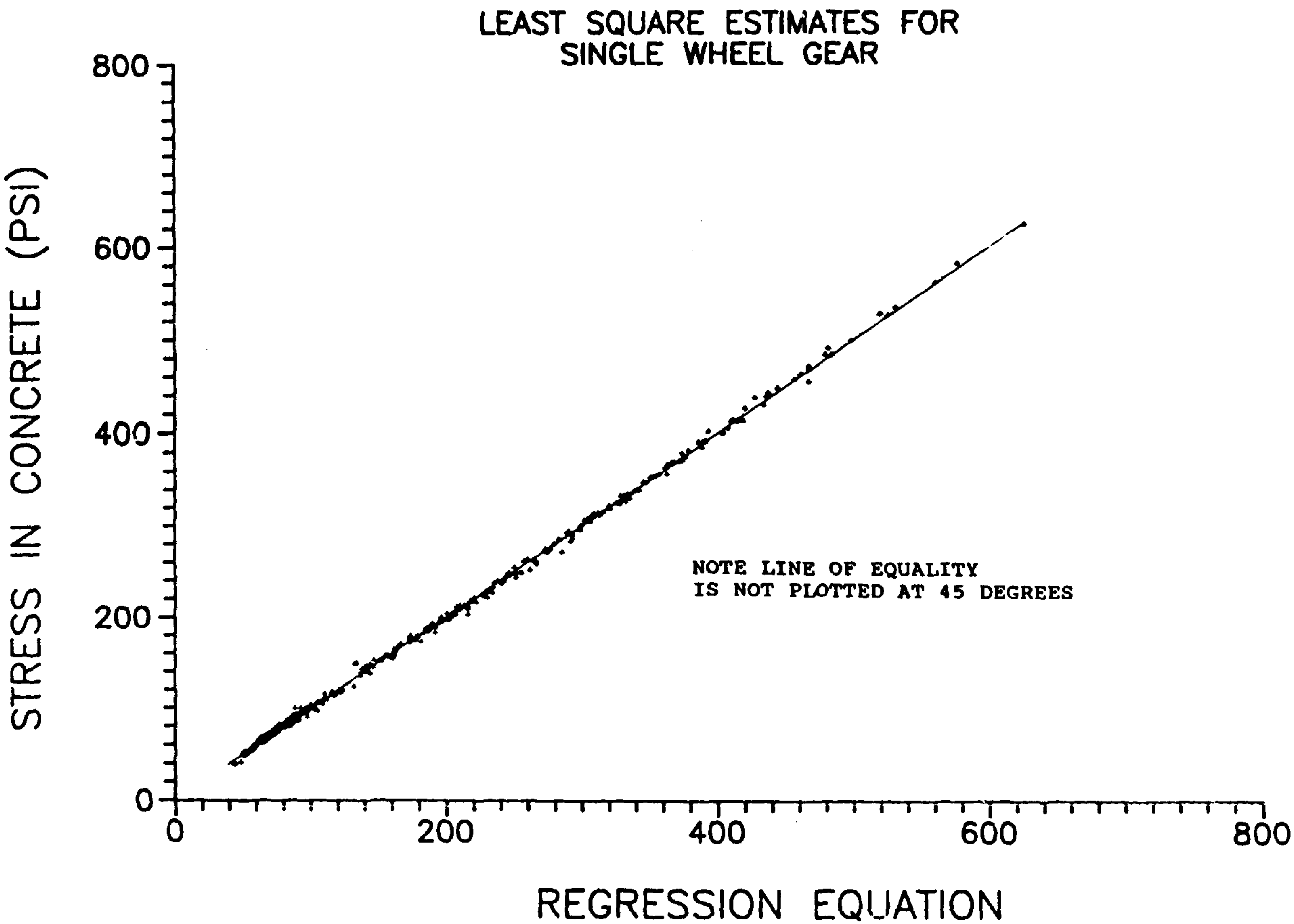


Figure 29. Comparison of predicted versus actual stress values for the case of a single-wheel gear (two-rigid layer system)

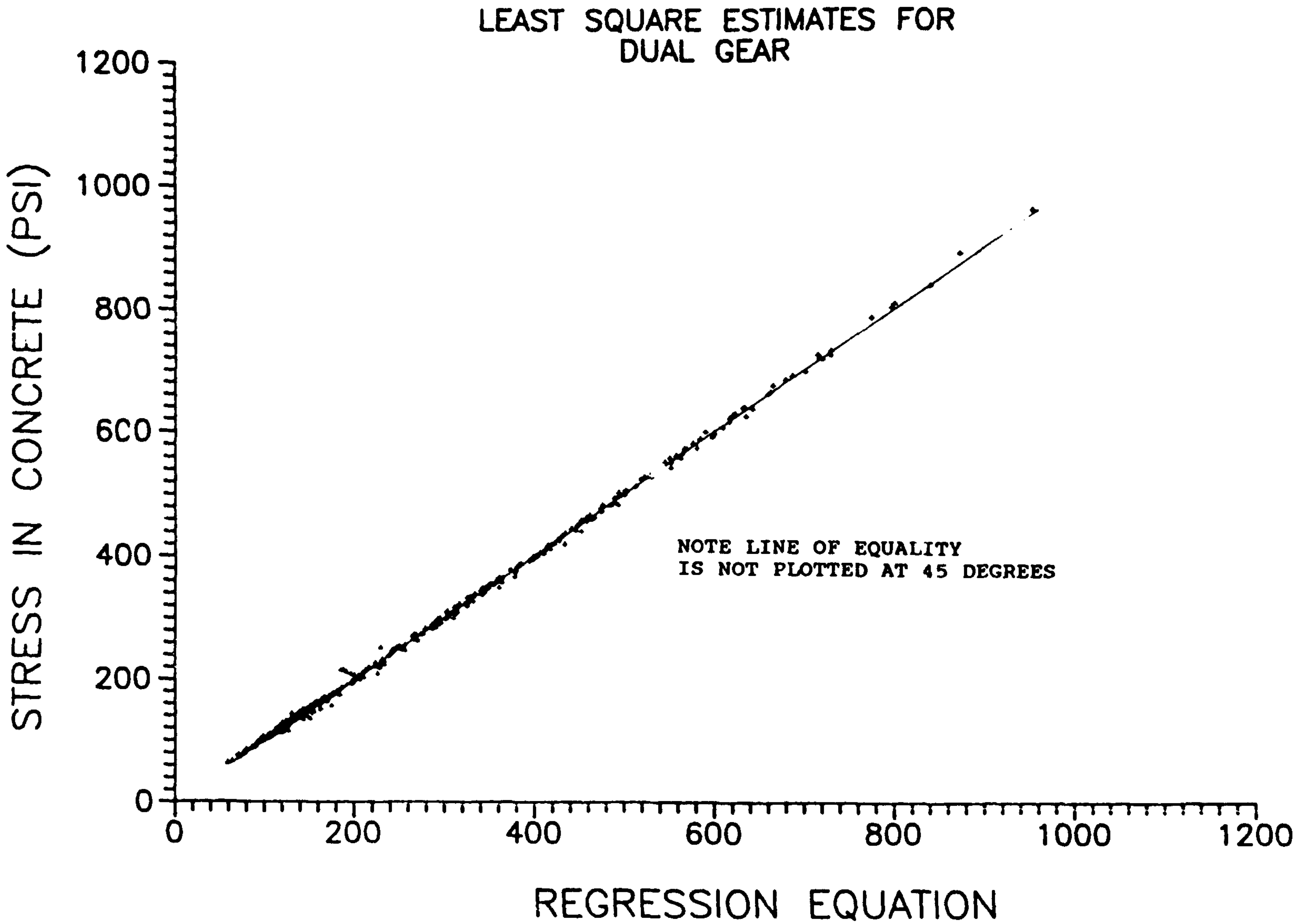


Figure 30. Comparison of predicted versus actual stress values for the case of a dual-wheel gear (two-rigid layer system)

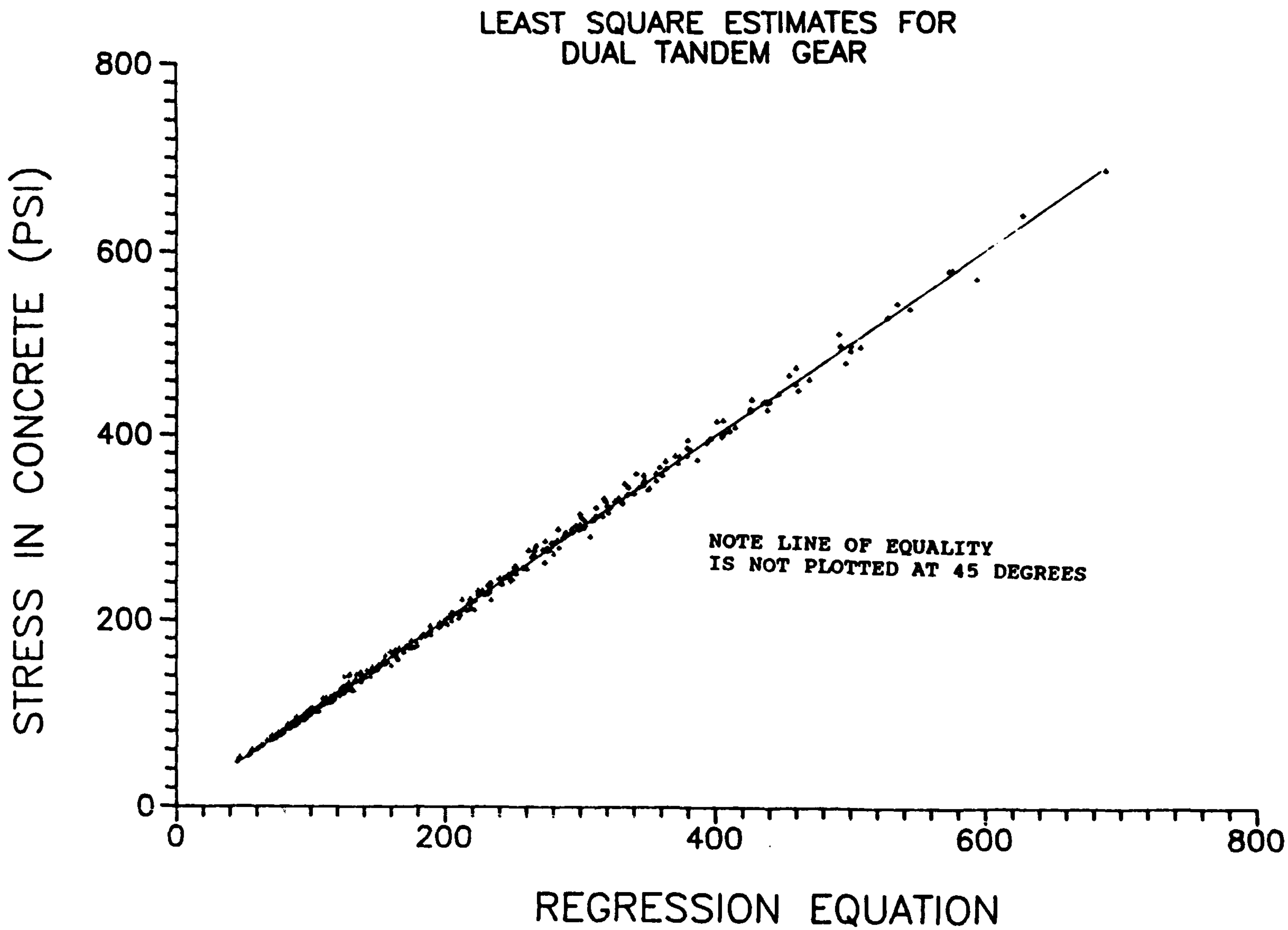


Figure 31. Comparison of predicted versus actual stress values for the case of a dual-tandem gear (two-rigid layer system)

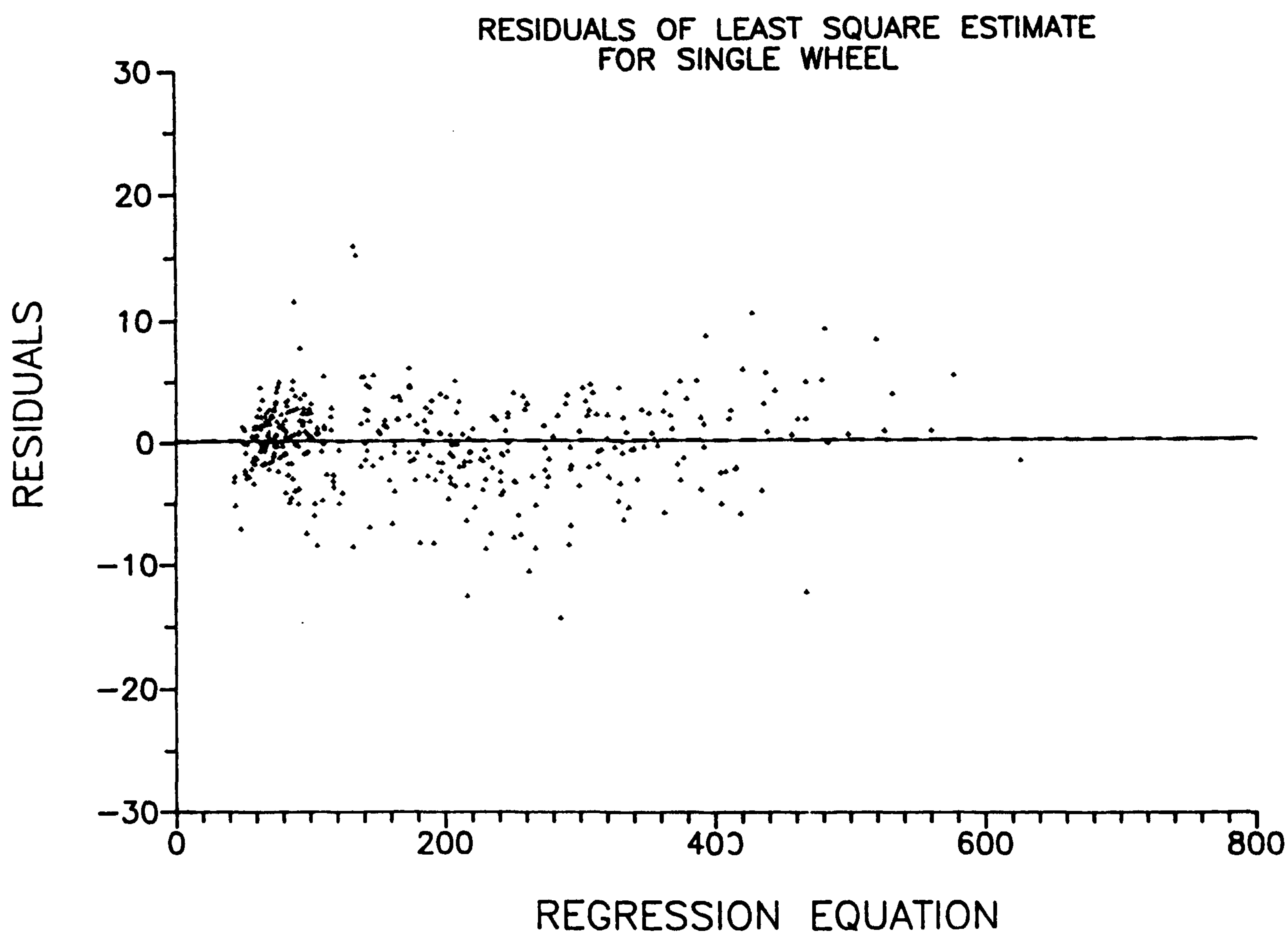


Figure 32. Residual plot obtained from the statistical model selected for the single-wheel gear (two-rigid layer system)

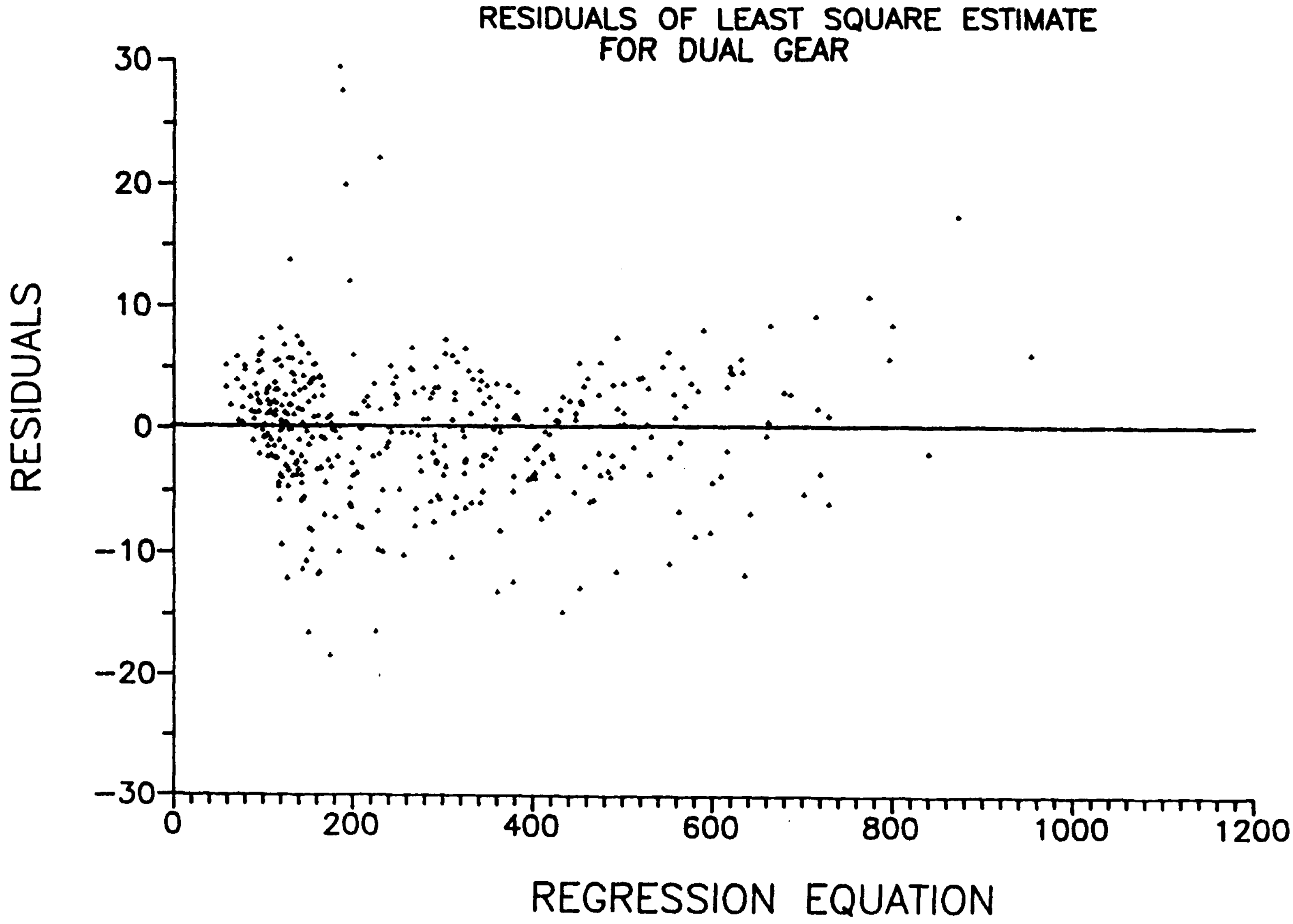


Figure 33. Residual plot obtained from the statistical model selected for the dual-wheel gear (two-rigid layer system)

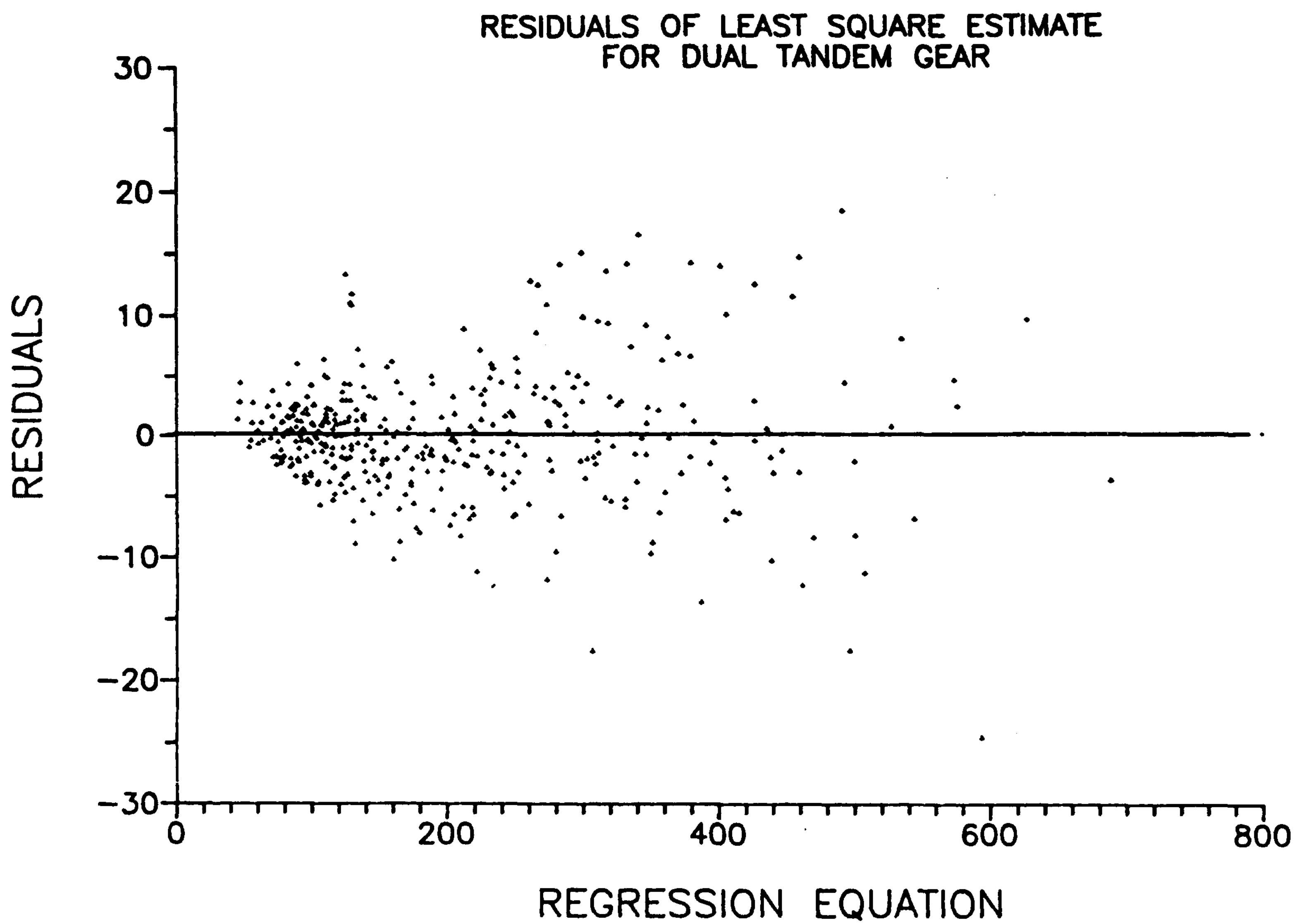


Figure 34, Residual plot obtained from the statistical model selected for the dual-tandem gear (two-rigid layer system)

Table 3

Regression Coefficients, Interior Stress in the CTB for the Two-Rigid Layer System

REGRESSION COEFFICIENTS	GEAR TYPE		
	SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	-1.54962E-04	-1.14871E-04	-9.69983E-05
a2	-.09001	-0.08893	-0.09306
a3	0.32334	0.33870	0.36498
a4	-0.02994	-0.02350	-0.02921
a5	-0.01850	-0.01829	-9.29258E-03
a6	-6.82371E-03	-7.46144E-03	-8.35922E-03
a7	-7.93621E-03	-7.78525E-03	-7.47100E-03
a8	2.778992E-04	5.404066E-04	7.70275E-04
a9	22.59014	20.06895	17.86815
a10	0.47821	0.46020	0.45719
a11	-0.15486	-0.12404	-0.08699
a12	-22.51655	1.92671	-23.879356
Constant	1.57794	-388.66280	1.46192
R2	0.99827	0.99852	0.99772
Standard Error, psi	0.03965	0.03443	0.03970
Standard Error, % error	1.11	0.84	1.0

The maximum standard error was equal to 1.11 percent of the logarithmic mean of the stress values. A high degree of correlation was observed between the predicted and computed stress values as indicated by the high R^2 values. Figures 35 through 37 show the close agreement between the predicted and computed stresses. Residual plots presented in Figures 38 through 40 do not show any trends but indicate a small error over the range of the regression.

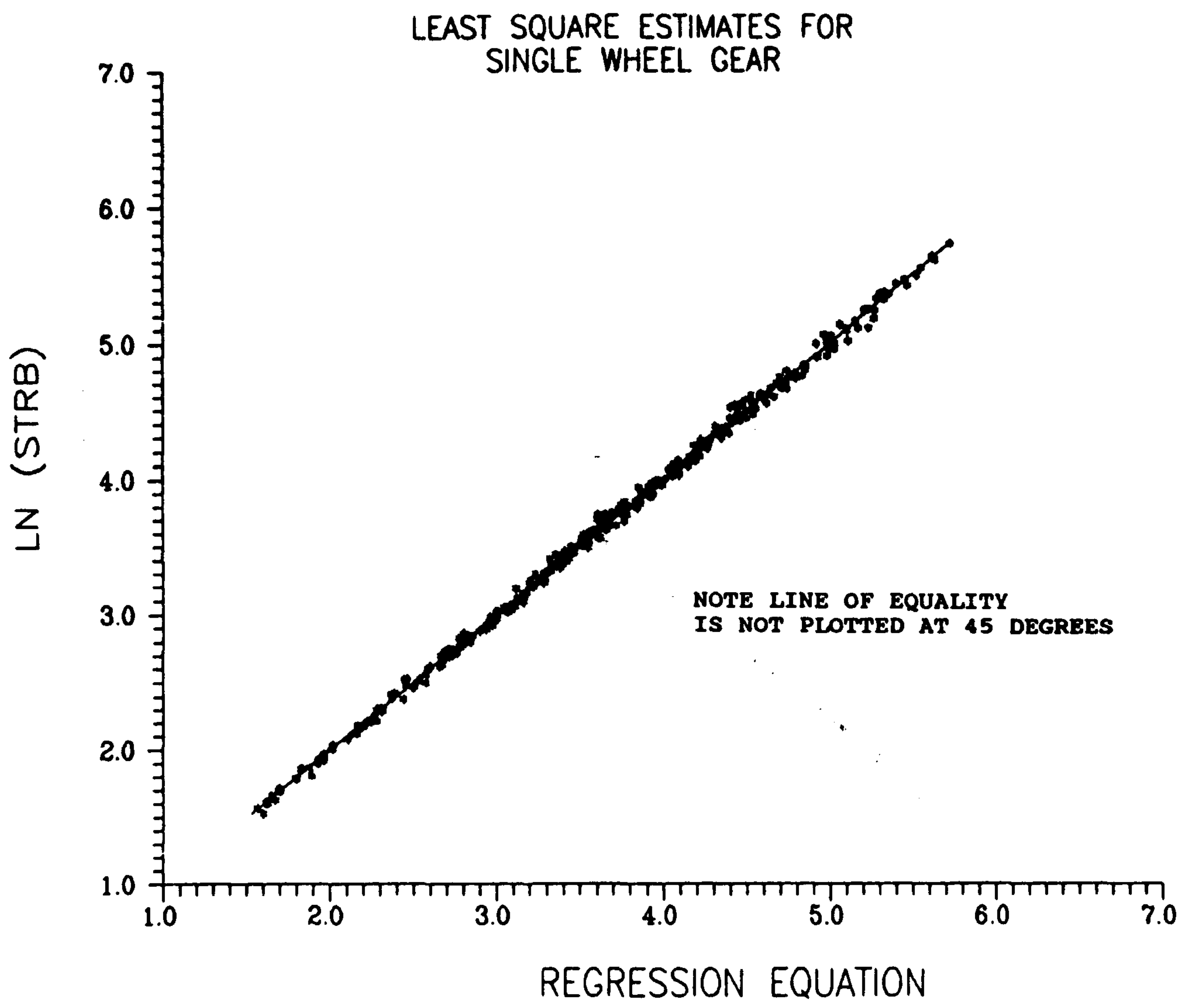


Figure 35. Comparison of predicted versus actual stress values for the case of a single-wheel gear (two-rigid layer system)

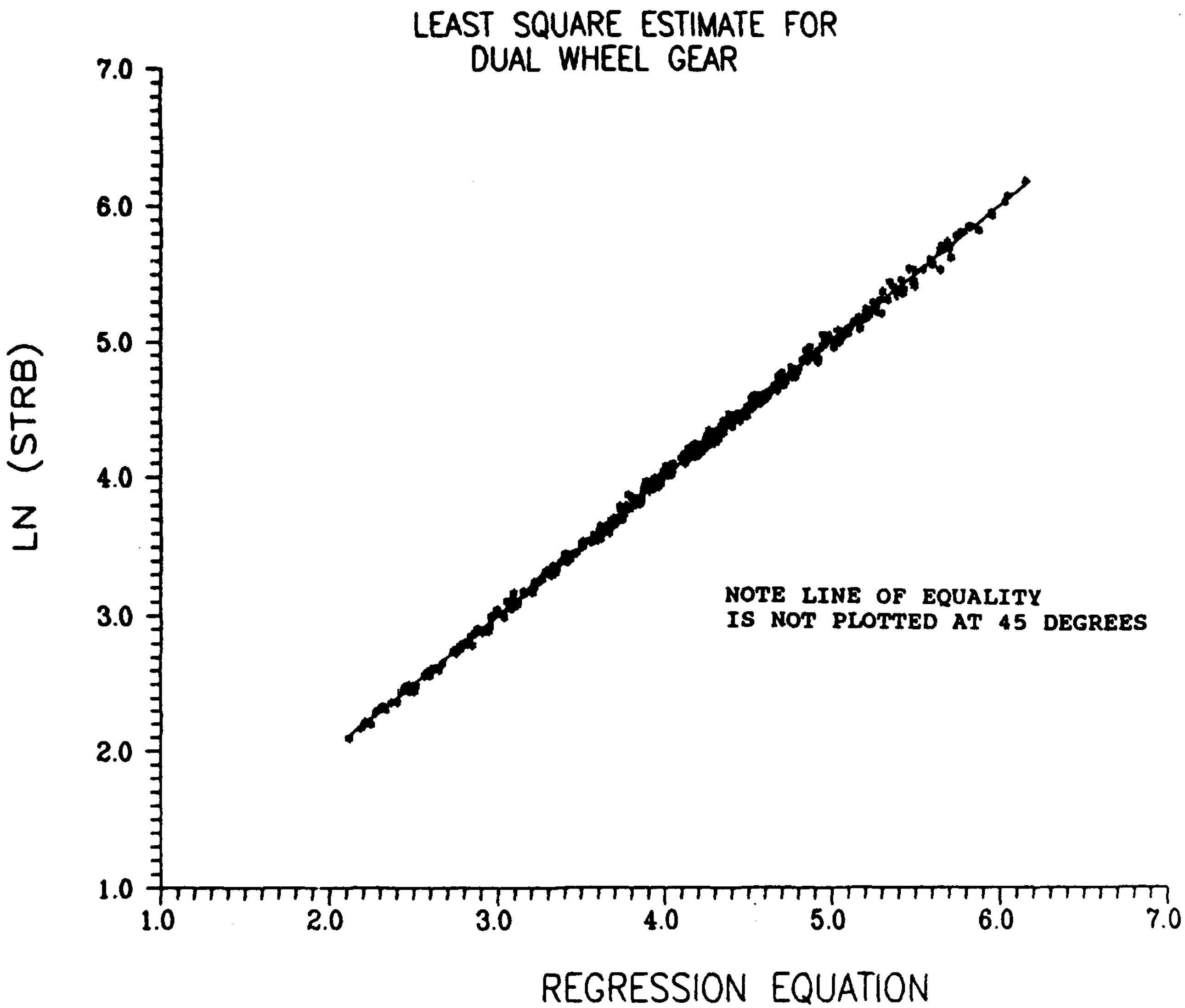


Figure 36, Comparison of predicted versus actual stress values for the case of a dual-wheel gear (two-rigid layer system)

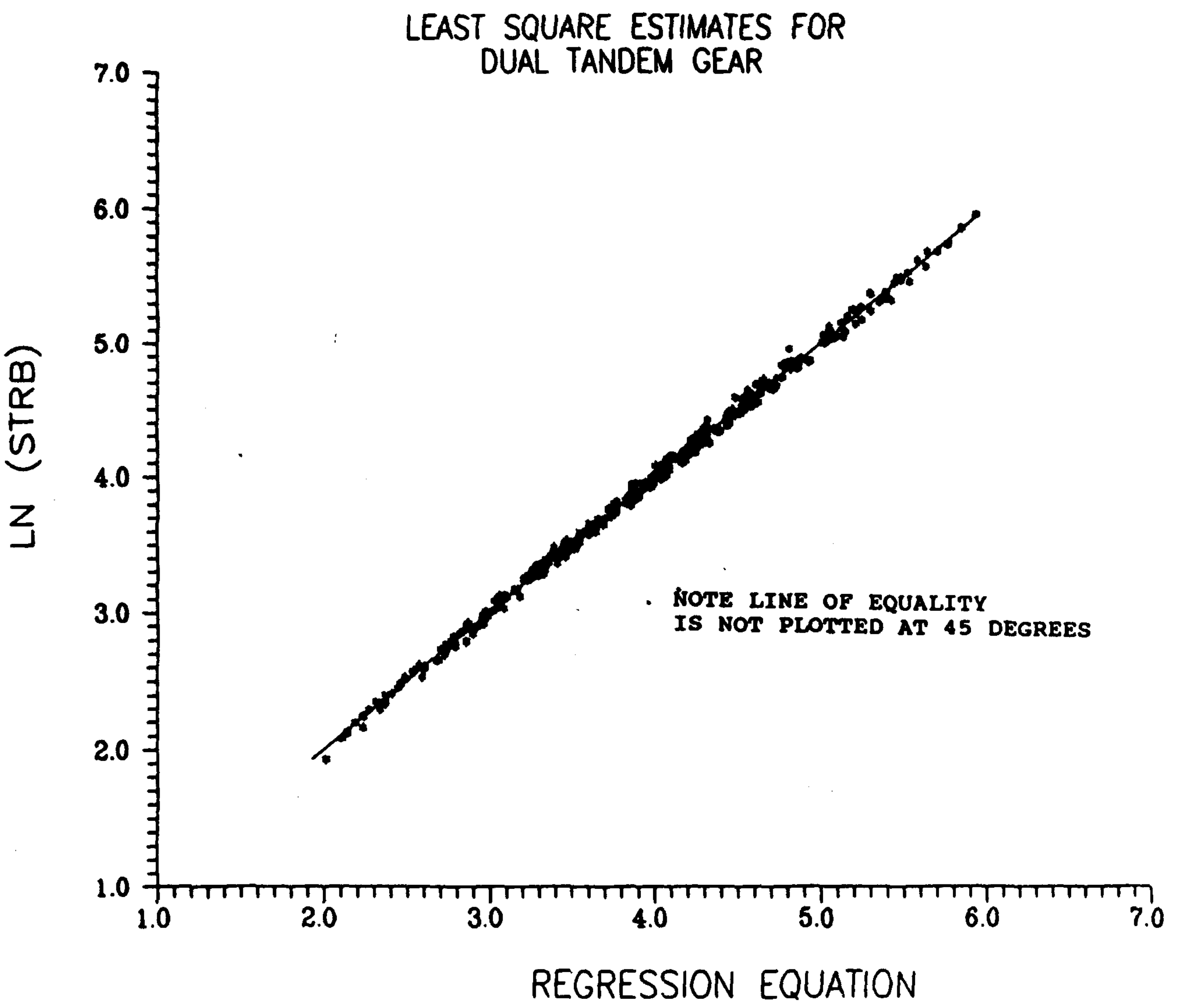


Figure 37. Comparison of predicted versus actual stress values for the case of a dual-tandem gear (two-rigid layer system)

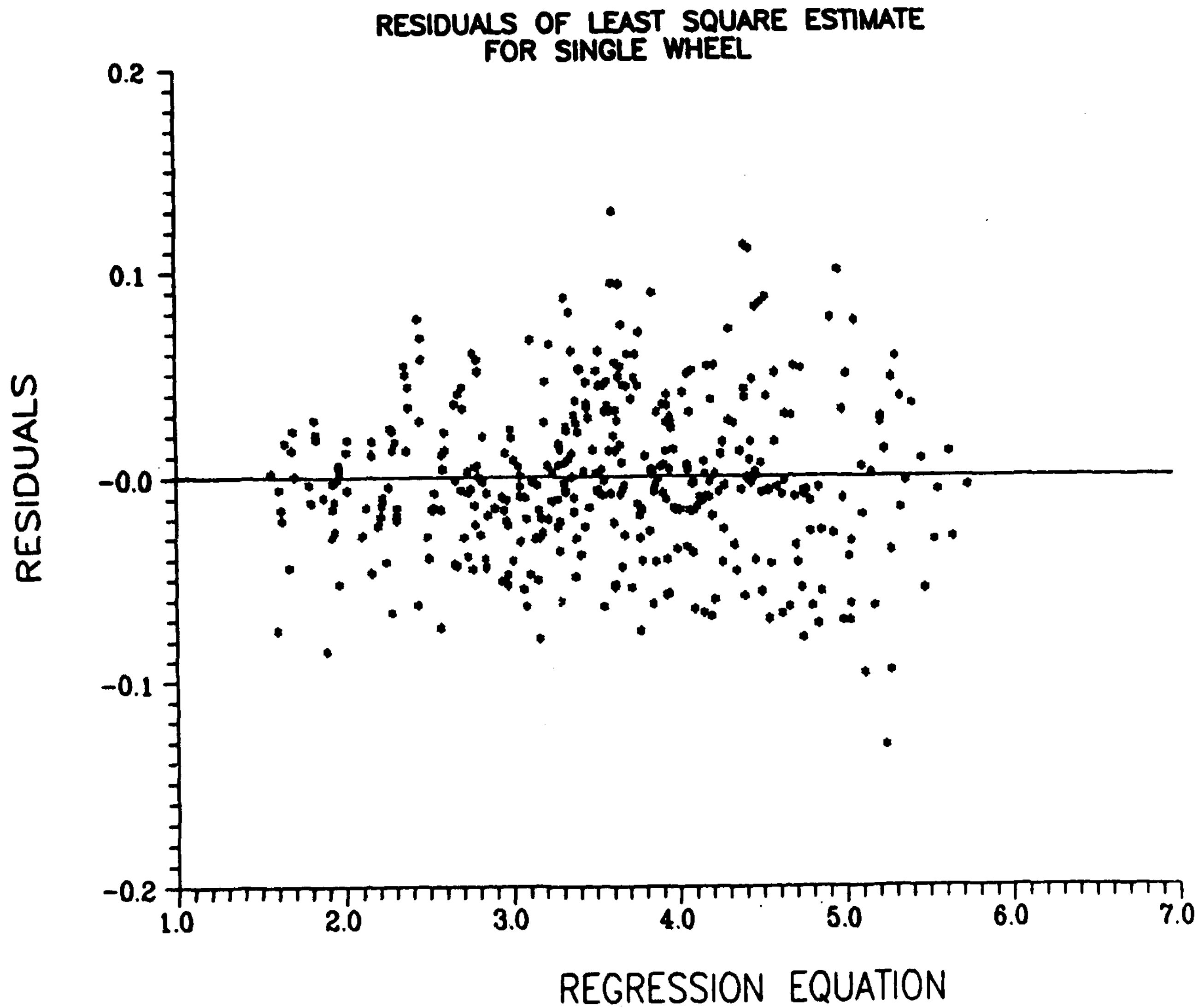


Figure 38. Residual plot obtained from the statistical model selected for the single-wheel gear (two-rigid layer system)

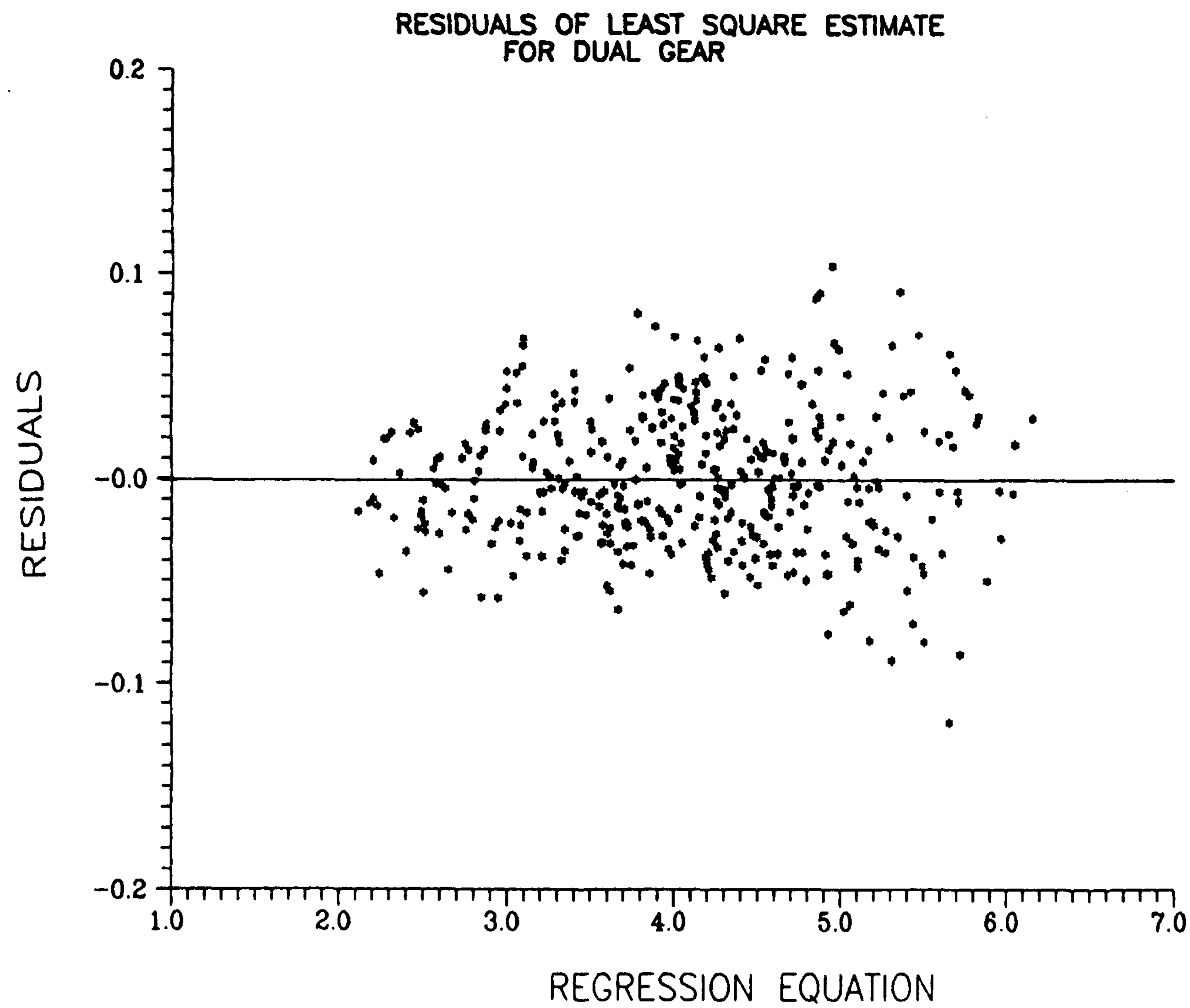


Figure 39. Residual plot obtained from the statistical model selected for the dual-wheel gear (two-rigid layer system)

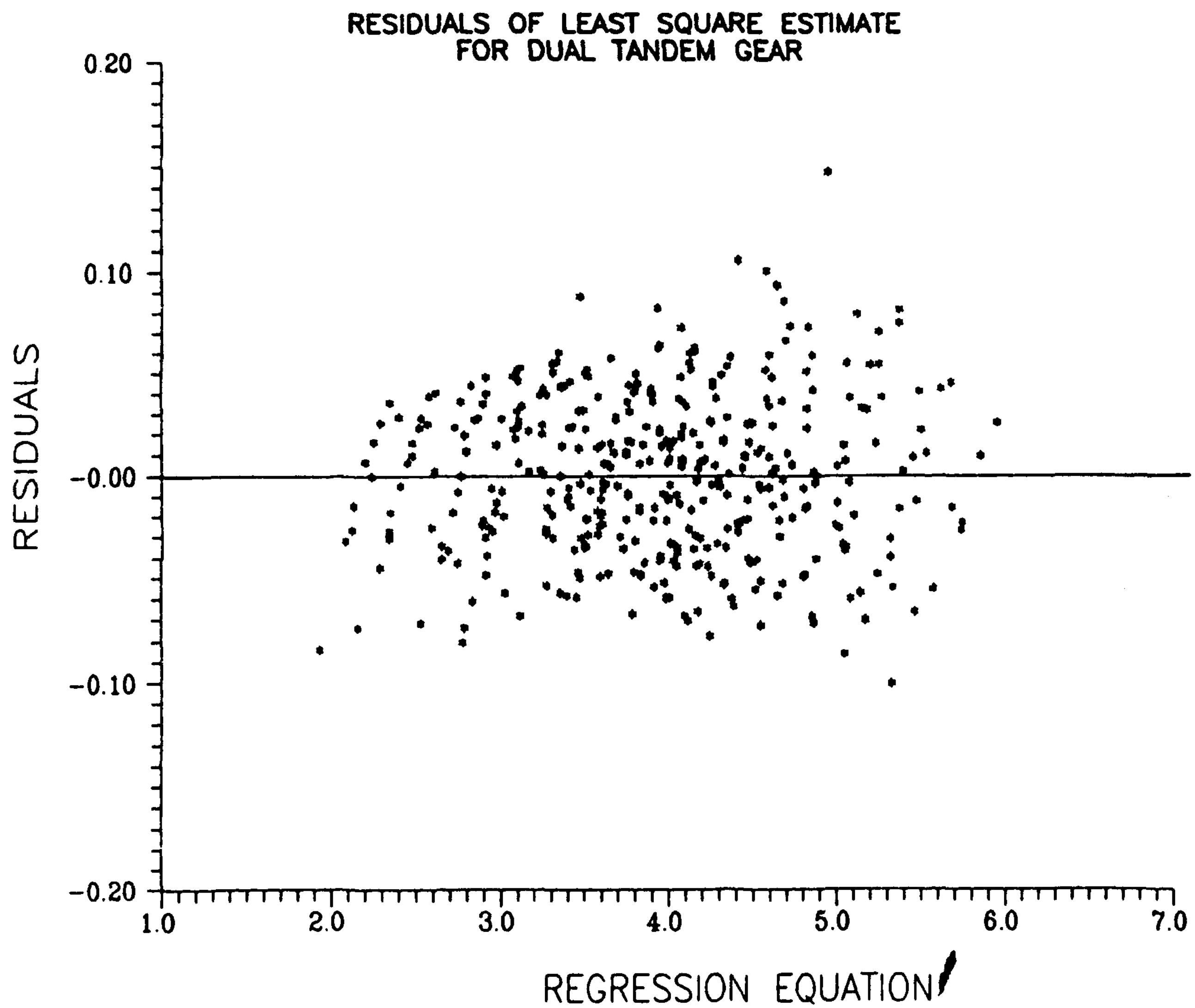


Figure 40. Residual plot obtained from the statistical model selected for the dual-tandem gear (two-rigid layer system)

Load Effects

The factorial design did not include the aircraft load as one of the major factors. Since BISAR was the selected behavior model; linear elasticity is assumed. However, problems could arise through the interaction of two factors. Partial interface slip conditions were used in the analysis. This fact alone would not cause nonlinear behavior. Coupled with the fact that the maximum tensile stress was used could, however, develop some problems with regard to positional change of the maximum load. If these factors did cause positional shifts, a modified equation for loading conditions would be necessary. To validate the linearity assumption, two factorials were analyzed using BISAR--one for the concrete (surface layer) and the other for the cement-treated base. Primarily, the boundaries of the original factorial were searched. These areas were found to contain the elements of positional shifts in the original computer runs.

The results of these runs are presented in Tables 4 and 5. The tables present the ratio of the maximum tensile stress determined at the full- and half-load limits. As shown, the ratio of the stresses calculated for the full- and half-load case is nearly constant at a value of 0.5. Thus, the assumption of linearity is not interfered with due to the positional and friction factor considerations.

Summary

Although the selected regression equations contain a large number of variables to reduce the error in prediction, most of the variables are used in current design procedures and are easy to compute. In addition, a microcomputer program will be provided to solve efficiently the regression equations and to select the required base/surface thicknesses for a particular foundation and loading condition.

The errors associated with the regression equations are judged to be acceptable for all practical design purposes.

Table 4

Stress Comparison at Load = P and Load = P/2 (Concrete Slab)

Subgrade Modulus, ksi		5								30							
CTB Modulus, ksi		250				2500				250				2500			
HC, in.		8	8	26	26	8	8	26	26	8	8	26	26	8	8	26	26
HCTB, in.		4	22	4	22	4	22	4	22	4	22	4	22	4	22	4	22
Gear Type	Load Type																
DUAL	P/2	481.000	238.000	79.300	62.900	349.000	69.200	66.000	32.700	332.000	216.000	61.400	51.500	267.000	72.000	53.500	30.100
	P	959.000	476.000	156.000	124.000	696.000	140.000	132.000	65.200	659.000	432.000	122.000	103.000	532.000	146.000	107.000	60.100
STRESS RATIO		0.502	0.500	0.508	0.506	0.501	0.494	0.506	0.502	0.504	0.500	0.503	0.500	0.502	0.499	0.500	0.501
DUAL TANDUM	P/2	342.000	171.000	75.100	57.400	246.000	42.400	61.300	25.700	218.000	150.000	51.200	42.100	179.000	47.900	43.800	22.300
	P	685.000	343.000	150.000	115.000	492.000	84.700	123.000	51.400	436.000	301.000	103.000	84.300	358.000	95.700	87.700	44.700
STRESS RATIO		0.499	0.499	0.501	0.499	0.500	0.501	0.498	0.500	0.500	0.498	0.497	0.499	0.500	0.501	0.499	0.499

Table 5

Stress Comparison at Load = P and Load = P/2 (CTB)

		E sub, ksi		5		30
		ECTB. ksi		250		2500
		HC, in.	8	26	8	26
		HCTB, in.	4	22	4	22
GEAR TYPE	LOAD TYPE					
	P/2		46.900	6.500	167.000	22.700
DUAL	P		93.700	13.000	314.000	45.400
	STRESS RATIO		0.501	0.500	0.500	0.500
	P/2		34.800	8.000	108.000	22.200
DUAL TANDUM	P		69.600	16.100	217.000	44.500
	STRESS RATIO		0.500	0.499	0.498	0.499

DEVELOPMENT OF THE DESIGN PROCEDURE

This section describes the assumptions made, the limitations, and the steps involved in the new design procedure. This section will also include descriptions of two microcomputer programs provided to perform the design of new rigid pavements and/or the evaluation of existing pavements.

The new design method was developed to supplement existing rigid pavement design methods used by the FAA and not to replace them. The new method is based on providing a two rigid layer pavement structure equivalent in terms of performance to the concrete slab (one rigid layer) designed using current FAA procedures. The equivalence between the two pavement structures is achieved by equating the maximum tensile stress in the concrete slab without exceeding the tensile strength of the CTB.

Assumptions

Current rigid pavement design procedures are based on limiting the maximum tensile stress at the edge of the pavement. The critical stress condition occurs when the load is located as close as possible to the edge of the pavement. However, because BISAR uses elastic theory to compute the pavement's behaviour to loading, the edge loading condition could not be modeled. This limitation arises from an assumption made by the elastic theory, namely, the pavement dimensions extend to infinity in the horizontal plane. For this reason, interior stresses were evaluated instead of edge stresses. The main assumption made during the course of developing this design procedure is that similar performance will be achieved by equating the maximum interior tensile stress at the bottom of the concrete layer in both pavement structures. If the maximum interior tensile stress is equal in both pavement structures, the maximum edge tensile stress is also equal in both pavement structures.

Another limitation to this design procedure is that the method is valid only within the range of the factorial design. This limitation arises from the use of regression analysis to predict the required pavement response. However, the same approach can be used if the stress can be accurately predicted outside the range of the factorial design using such methods as elastic theory.

Strength and failure criteria of the CTB have been obtained from limited published data. These relationships should be modified as more data become available.

Input Requirements

The design variables required for the new design method are similar to those required by the current FAA procedure. These variables are listed below:

a. Traffic in aircraft departure per year

b. Aircraft type

c. Gross aircraft load, P

d. Modulus of rupture of the concrete, Mr psi

e. Modulus of subgrade reaction, K in pci

The strength property of the CTB (i.e. modulus of rupture) is an additional input required by the new method.

The factorial design performed using the BISAR computer program required elastic material properties to compute the tensile stresses in both rigid layers. Therefore, relationships were needed to transform K of the subgrade and Mr of the CTB into elastic moduli. These relationships are listed below:

$$K = 10(\log[E_{sub}]-1.415)/1.284 \qquad (6)$$

$$E_{ctb} = [\mathrm{Ln}\ (UC) - 7.0] \ / \ 3.597E\text{-}4 \ ,(Ksi) \qquad (7)$$

$$Mr_{ctb} = 218.2\ EXP^{(3.597E\text{-}07*E_{ctb})} \qquad (8)$$

E_{sub} = subgrade resilient modulus, psi

UC = unconfined compressive strength of CTB, psi

E_{ctb}, MR_{ctb} = modulus of elasticity and modulus of rupture of the CTB, psi

K = Modulus of subgrade reaction, pci

An example design is performed for the following factors:

a. Gear type = dual tandem

b. MR of concrete = 700 psi

c. K of subgrade = 150 pci

d. CTB compressive strength = 2,000 psi

e. Number of annual departures = 25,000

f. Gross aircraft load = 380 kips

The modulus of rupture of the CTB is related to the compressive strength by the following relationship:

$$MR_{ctb} = UC/5 \qquad (9)$$

The next step is to determine the concrete thickness using FAA rigid pavement design procedure. The procedure for rigid pavement design is presented in an Advisory Circular (AC No. 150/5320-6C) dated December 7, 1978. Using the input requirement stated above, with the exception of the CTB strength property, a concrete thickness can be selected. A design chart is used for each gear type. Knowing the design modulus of rupture of the concrete, the gross load of the aircraft, the modulus of subgrade reaction, and the number of annual departures, the design thickness can be determined from the selected design chart (see example in Figure 41).

Evaluation of the tensile stress condition in the concrete slab of a one-rigid layer pavement system is the next step. After selecting the slab thickness, the maximum tensile stress can be determined using the regression equations developed in this study. Three equations are provided for three different gear types: single wheel, dual wheel, and dual tandem gears. Several computational steps are required prior to entering the regression equations since some of the variables in these equations are functions of the input variables described in the previous paragraph. Such functions include the radius of relative stiffness, L

a. Compute L

$$L = \sqrt[4]{\frac{E_{conc} * H_{conc}^3}{12(1-u^2)K}}$$

where

E_{conc} = Elastic modulus of the concrete, psi

H_{conc} = Design concrete thickness, in

u = concrete poisson's ration (= 0.15)

K = modulus of subgrade reaction, pci

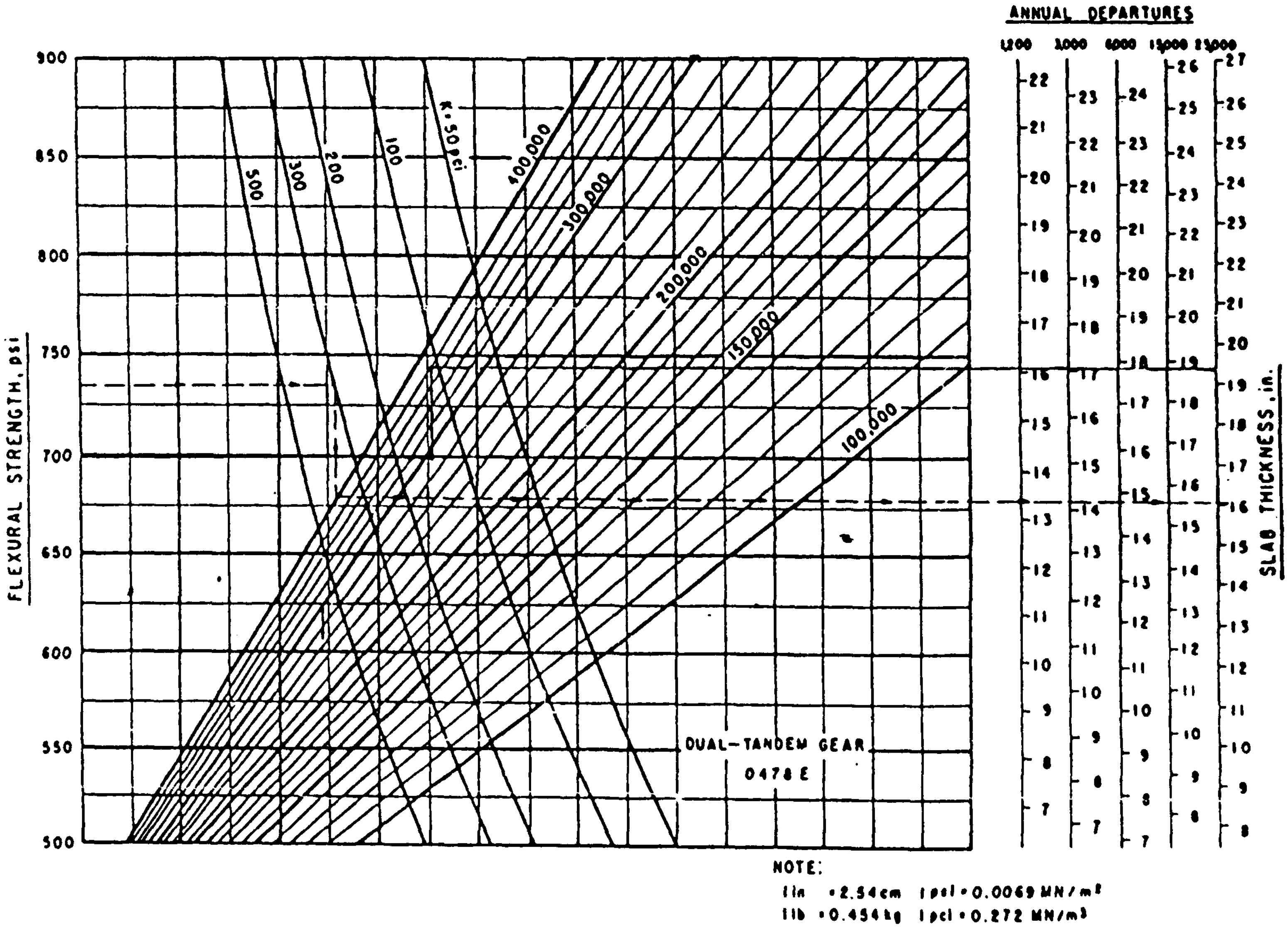


Figure 41. Typical design chart used to select the required concrete slab thickness for given loading and soil support conditions (FAA Des. Meth., AC No. 150/5320-6C)

b. Use the following relationships to determined subgrade properties $K = 10^{(\log[E_{sub}] - 1.415)/1.284}$, or

$$E_{sub} = 10^{(1.284 \log[K] + 1.415)}$$

c. Determine maximum tensile stress in one rigid layer system using regression equations

$L = 63.8$ in

$E_{sub} = 16,185$ psi

$Sc = 325$ psi (from regression equations)

d. Assume concrete and CTB thicknesses and evaluate stress condition in the concrete slab of the two-rigid layer pavement system

Initial rigid layer thicknesses are selected and used to compute the maximum tensile stress in the concrete slab. Equation 2 is used in the process. Several intermediate computational steps are required prior to entering the regression equations. In addition, the gear type is required to select the appropriate regression coefficients. Some of the computational steps involved are listed below:

(1). Compute modular ratios:

$Er_1 = E_{conc}/E_{ctb}$

$Er_2 = E_{c\smile\omega}/E_{sub}$

(2). Compute radius of relative stiffness for each of the rigid layers assuming each layer is supported directly by the subgrade:

$$L_1 = \sqrt[4]{\frac{E_{conc} * H_{conc}^3}{12(1-u^2)K}}$$

$$L_2 = \sqrt[4]{\frac{E_{ctb} * H_{ctb}}{12(1-u^2)K}}$$

where,

E_{conc}, E_{ctb} = modulus of elasticity of the concrete and CTB in psi, respectively

u = Poisson's ratio of the concrete and CTB materials.

E_{ctb} = 1,684,000 psi

Assume H_{conc} = 11.5 H_{ctb} = 10

Er_1 = 2.394

Er_2 = 103.1

L_1 = 43.1 in.

L_2 = 31.3 in.

S_{conc} = 249 psi S_{ctb} = 192 psi

e. Check for equality of maximum tensile stress between the rigid pavement systems

The maximum tensile stress in the two pavement structures are compared. If these stresses are within $\pm$ 2.5 psi, then the selected concrete and CTB thicknesses will provide equivalent performance to the one-rigid layer pavement system designed using the FAA procedure. If the stress difference is outside the allowable range, new concrete and CTB thicknesses are assumed and step d is repeated. This process is continued until convergence is obtained. In general, convergence is achieved within three iterations. The result of this step is the selection of layer thicknesses meeting the stress equality criteria. An example of such criteria is as follows:

FAA design: H_{conc} = 19.4 in.

Stress in concrete layer = 235 psi

Select : H_{conc} = 11.5 in.

H_{ctb} from new design = 10.0 in.

Stress in concrete layer = 249 psi

249 >235 psi => repeat step d

Select: H_{conc} = 11.4 in, H_{ctb} = 11.0 in.

Stress in concrete = 234 < 235 psi => acceptable.

f. Check for maximum tensile stress in CTB

The new design method is based on a fixed condition of the CTB. It is assumed that the condition of the CTB will remain constant over the life of the pavement. Therefore, a limit is set against fatigue failure of the CTB. For the lack of any other published data, the PCA fatigue failure for concrete pavement is criterion applied to the CTB. This criterion states that the slab can resist an infinite number of load applications provided the stress ratio, i.e. maximum tensile stress in the CTB divided by the modulus of rupture of the CTB, remains below 0.5.

The following failure criterion obtained from Thompson[10] is used to determine the number of allowable load repetitions if the stress ratio is greater than 0.5:

$$\text{Log}(N) = [(0.972 - SR)/0.0825] \quad (10)$$

where

N = allowable load repetitions

SR = stress ratio, stress divided by MR

It is recommended that the stress ratio be always kept under 0.5 for the final selection of the layer thicknesses. At the present time, the limit on the value of the stress ratio is not a limiting criterion. However, as more data becomes available regarding the fatigue behavior of the CTB, the limiting criterion should become a controlling factor in the final selection of the layer thicknesses. This is shown in the following example.

H_{conc} = 11.5 in., H_{ctb} = 11.0 in.

S_{ctb} = 181.2 psi

SR = .453 => acceptable.

Disadvantages of the new method

Two disadvantages were noted in the application of the new design method. The first disadvantage is the tedious calculations involved in the manual solution of the regression equations. This disadvantage stems from the large number of terms included in the regression equations. In addition, the trial-and-error procedure involved in the final selection of the layer thicknesses in order to meet the allowable stress difference between the one-and two-rigid layer pavement systems is very time-consuming.

To eliminate this disadvantage, microcomputer programs have been developed. A description of the programs is provided in the next section.

The second disadvantage is that of layer thickness selection. The selection of the layer thicknesses is not unique since the stress equality between the two pavement systems can be obtained for different layer thicknesses and layer material properties. Therefore, the optimum solution will depend on the judgment of the engineer performing the design.

Computer Programs

The time required in the manual selection of the concrete slab and CTB thicknesses using the new design procedure is examined. This fact has been recognized in the previous paragraph as one of the main disadvantages of the new design methods. To alleviate this problem, two computer codes are provided to automate the new design

A description of both programs is provided in the following sections.

General Description

The two computer codes, CTBDES and CTBEVL, are interactive programs which are used to design or evaluate two-rigid layer pavement systems. The programs solve the regression equations obtained from the large factorial design. The source codes are written in the BASIC computer language and are suitable for use with an IBM-compatible microcomputer. Both source codes are included in Appendix C. Minor changes may be required to the source codes, particularly in input/output operations such as opening and closing files, in order to be used on other computer systems.

DESCRIPTION OF CTBDES

CTBDES is used to select the concrete and CTB slab thicknesses. The main difference between CTBDES and CTBEVL is that the first program provides all concrete-CTB thickness combinations that satisfy the maximum tensile stress equality criteria described earlier in this report. All concrete and CTB thicknesses within the valid range of the regression equations are evaluated. Figure 42 presents the flow chart of CTBDES. The same steps involved in the hand computations, which were described earlier in this SECTION, are followed by the program.

The input requirements include the concrete slab thickness obtained from the current FAA design procedure for

a given aircraft type and design gross load, and the subgrade, and CTB strength properties. Figure 43 illustrates an example of the input requirements for CTBDES. The computer code has been structured such that more than one strength property can be used to characterize a given layer of the pavement system. For example, the modulus of subgrade reaction, K, or the resilient modulus of the subgrade, E_{sub}, could be entered. Similarly, the compressive strength or the elastic modulus of the CTB could be entered.

Figure 44 presents an example of the output obtained from CTBDES. The user input is echoed in the top portion of the output. The subgrade and base properties which were not entered by the user and were needed for the solution of the regression equations are computed internally by the program using the relationships presented earlier in this section.

The concrete and CTB thickness combinations are presented in the lower portion of the output. The concrete slab thickness is increased by 1/2 in. for each step, and the required CTB thickness is determined. In addition, the maximum tensile stress in the concrete slab of the rigid layer pavement system (predicted) is compared with that of the one rigid layer pavement system (design).

The stress ratio in the CTB is also printed along with the resulting allowable load repetitions (i.e. passes).

DESCRIPTION OF CTBEVL

Figure 45 presents the flow chart followed by CTBEVL. The main purpose of CTBEVL is to select the required concrete thickness for an existing pre-selected CTB thickness. CTBDES was restructured as indicated on the flow charts to achieve this purpose. In general, similar outputs are obtained by both programs, except that only one concrete-CTB thickness combination exists for CTBEVL.

Design Comparison

The new design method developed to rationally select the required concrete and CTB thicknesses was presented in Section 5. This section describes a comparison between the results obtained by the new design method and those determined using the current FAA design method. The purpose of this comparison is to validate the results obtained by the new method and to study its sensitivity to changes in the design parameters.

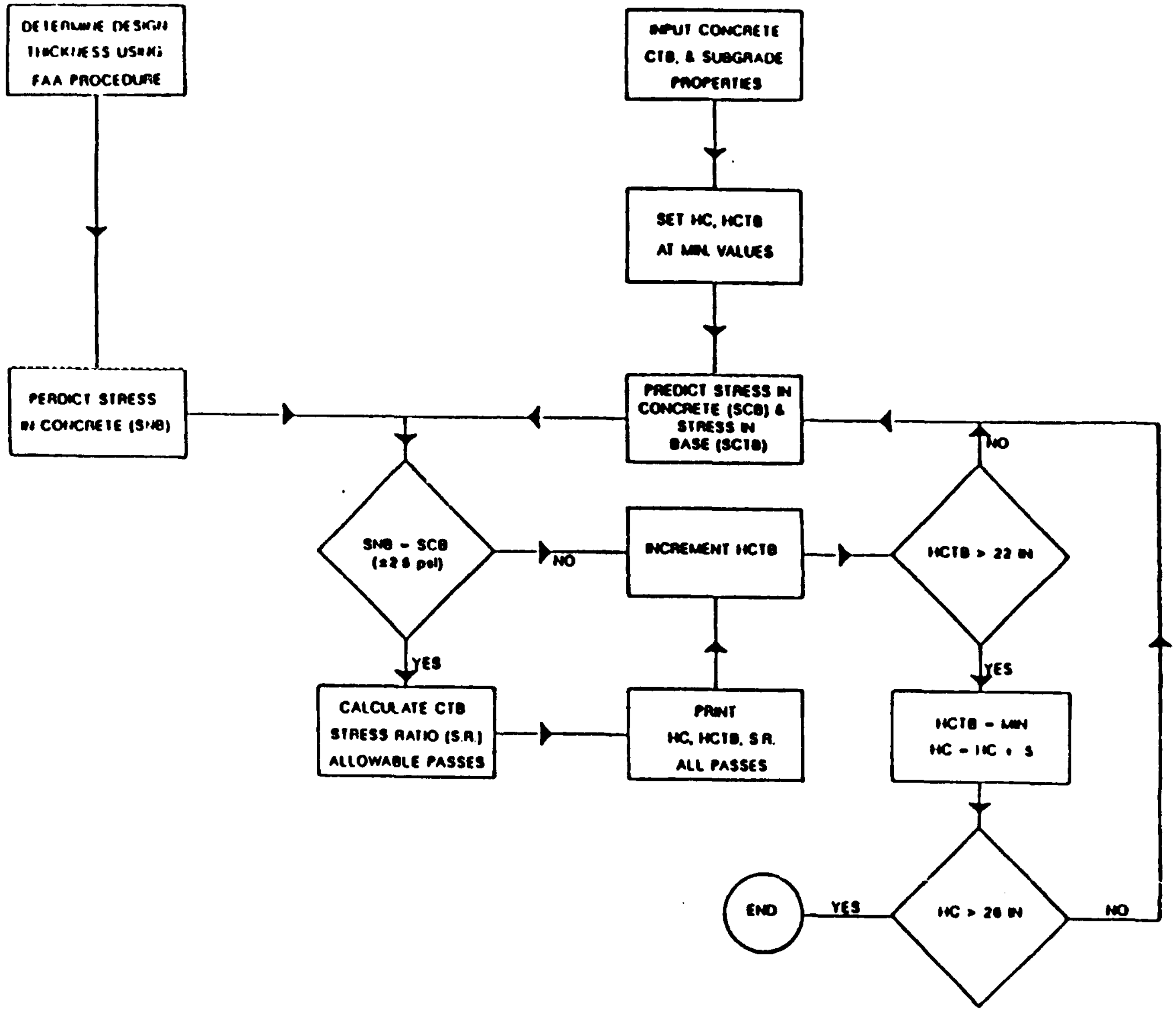


Figure 42. Flow chart for the CTBDES program

```
WHICH SUBGRADE PROPERTY DO YOU WANT TO USE (K OR E)? K
ENTER MODULUS OF SUBGRADE REACTION, K (PCI)? 150
WHICH CTB MATERIAL PROPERTY DO YOU WANT TO USE (FC OR E)? FC
ENTER COMPRESSIVE STRENGTH OF CTB (PSI)? 2000
ENTER DESIGN CONCRETE THICKNESS OBTAINED FROM FAA PROCEDURE (IN.)? 19.4
ENTER GEAR TYPE (SW,DT,DW)? DT
ENTER AIRCRAFT GROSS LOAD, P (KIPS)? 380
```

Figure 43. Example of input requirements for the CTBDES program

```
SUBGRAGE PROPERTIES - ESUB  (KSI) =        16.18457
                      K     (PCI) =        150
BASE PROPERTIES -     ECTB  (KSI) =        1684.584
                      FC    (PSI) =        2000
CONCRETE THICKNESS AS CALCULATED BY FAA DESIGN, HC (IN) =  19.40
GEAR TYPE :   DT
GROSS LOAD OF DESIGN AIRCRAFT, P (KIPS) =                 380
```

DETERMINATION OF CONCRETE AND CTB THICKNESS COMBINATIONS

THICKNESS (IN) CONC.	CTB	STRESS (PSI) PREDICTED	DESIGN	STRESS RATIO	ALLOWABLE PASSES
8.0	12.9	237	235	0.727	9.27E+02
8.5	12.8	237	235	0.673	4.17E+03
9.0	12.6	237	235	0.626	1.57E+04
9.5	12.5	235	235	0.584	5.11E+04
10.0	12.2	234	235	0.546	1.47E+05
10.5	11.9	234	235	0.512	3.80E+05
11.0	11.2	237	235	0.480	9.11E+05
11.5	11.0	234	235	0.453	1.97E+06
12.0	10.6	233	235	0.427	4.00E+06
12.5	10.0	233	235	0.404	7.69E+06
13.0	9.3	235	235	0.382	1.42E+07
13.5	8.8	233	235	0.362	2.45E+07
14.0	8.0	235	235	0.344	4.14E+07
14.5	7.5	233	235	0.327	6.62E+07
15.0	6.9	233	235	0.311	1.03E+08
15.5	6.2	233	235	0.296	1.57E+08
16.0	5.5	233	235	0.282	2.34E+08
16.5	4.7	233	235	0.268	3.41E+08

FOR THE LAST ITERATION:
HCTB IS < 4 IN. - USE HCTB= 4 IN. AND HC= 17 IN.

Figure 44. Example of the output obtained using CTBDES program

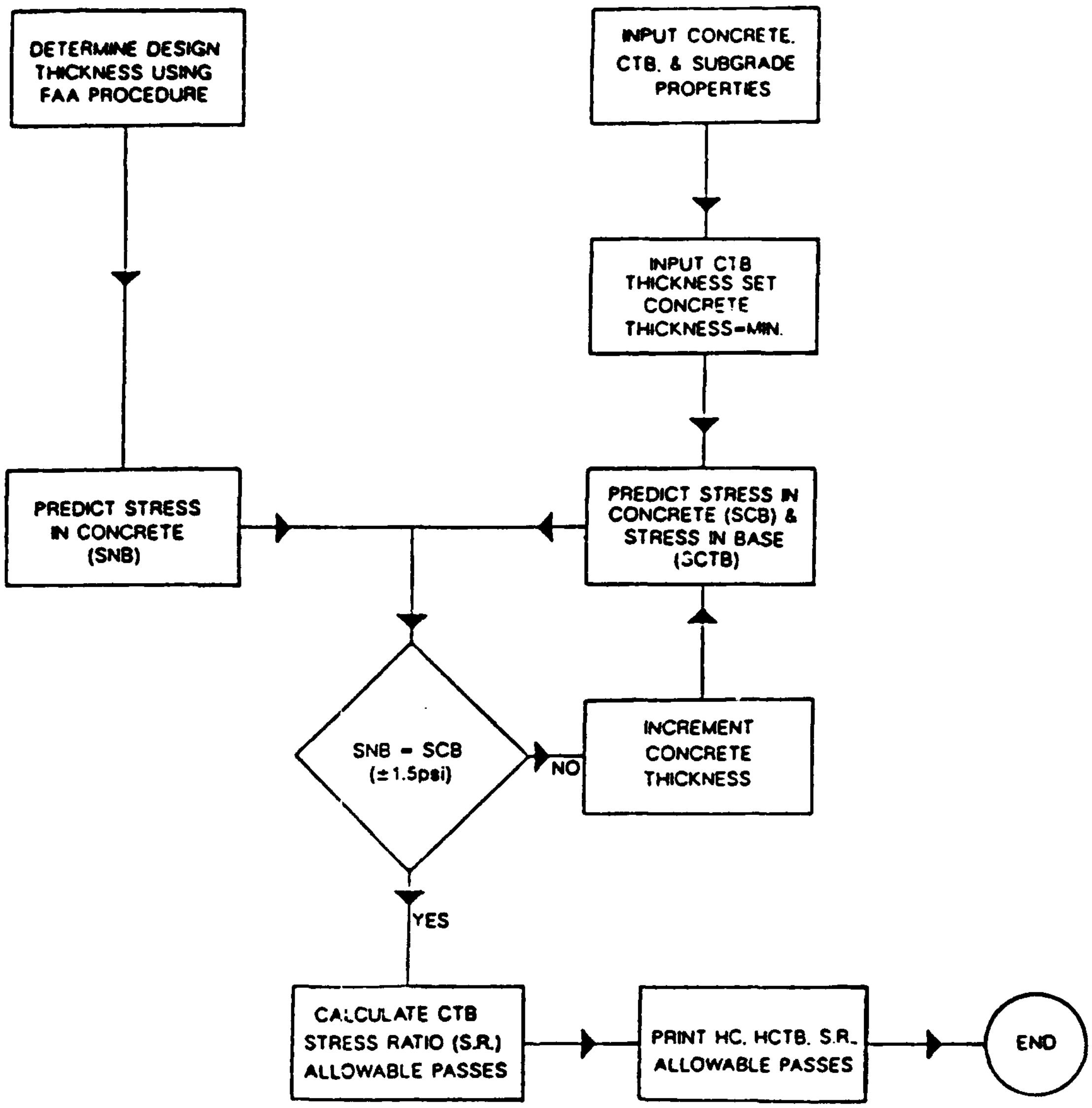


Figure 45. Flow chart for the CTBEVL program

Approach

A factorial design was selected to perform the comparison of the required concrete slab thickness as obtained by the two design methods. The factors and the levels of factors included in the factorial design are listed below:

a. Gear type: dual gear and dual tandem

b. CTB thickness: 6, 8 and 10 in.

c. CTB elastic modulus: 250, 500, and 1,000 ksi

d. Subgrade modulus: 5, 10, 20, and 30 ksi

e. Traffic level: 3,000, 15,000, and 25,000 annual departures

The current FAA design method cannot account for changes in the strength characteristics of the CTB in its determination of the subgrade support value. For this reason, a third design method was added to the comparison in order to evaluate better the capabilities of the new design method. The third design method uses a relationship developed by the US Army Corps of Engineers (CE) to compute a composite K of the subgrade and CTB which will then be used in the current FAA design method. The CE K-composite charts adjust for different CTB strength properties and thicknesses. However, K-composite cannot exceed 500 pci regardless of the strength or thickness of the CTB.

A total of 504 designs was performed as a part of this comparison.

New Design Method

The computer code CTBEVL was used to perform the computations. The results are listed in Table 6. These results indicate that the new method is sensitive to changes in the levels of the factors considered in the design. The required concrete slab thickness increases as the resilient modulus of the subgrade decreases and the traffic level increases. This relationship holds true for all combinations of the CTB thickness and CTB elastic modulus as well as for the two gear types. In addition, for a given gear type, traffic level, and subgrade strength, the required concrete slab thickness decreases as the CTB thickness and CTB elastic modulus increase.

The new design method does not set any limits on the structural value of the CTB provided that the CTB and subgrade material properties, the concrete, and CTB thickness combinations are within the valid range of the regression equations. The selected concrete slab thicknesses were based on providing a CTB stress ratio of 0.5 or less. Therefore, fatigue failure is not anticipated to occur in the CTB during the design life of the pavement structure.

FAA Method (K-composite determined from FAA chart)

This design method was performed according to the procedure included in the Advisory Circular AC 150/5320-6C, dated December 7, 1978. Using the K-composite chart provided in this manual, it is obvious that the design method is insensitive to changes in the elastic modulus of the CTB. However, all other relationships described in the previous paragraph also apply to this method. The results of this analysis are presented in Table 7.

FAA Method (K-composite determined from CE chart)

The K-composite chart developed by the CE was used in this method along with the design chart provided in AC 150/5320-6C for each aircraft type in order to determine the required concrete slab thicknesses. The results obtained from this method are listed in Table 8.

This method is insensitive to changes in subgrade and CTB material properties for thicknesses and moduli combinations producing K-composite values greater than 500 pci. The occurrence of this constraint in actual design cases is illustrated by the results of the analysis for CTB thicknesses of 8 and 10 in., subgrade moduli of 20 and 30 ksi, and CTB moduli of 500 and 1,000 ksi. For a given traffic level, the required concrete slab thickness is the same for any combination of the three variables listed above. Since the CE method is not dependent upon gear type, this condition is exhibited for both gears.

Table 6

Required Concrete Thickness as Determined by New Design Method

CTB Thick. (in.)	CTB Modulus (ksi)	Traffic Level (Dep./Yr.)	Dual Gear				Dual Tandem			
			Subgrade Elastic Modulus (ksi)							
			5	10	20	30	5	10	20	30
		3000	15.8	14.6	13.7	13.4	16.6	15.2	14.1	13.3
	250	15000	17.4	16.2	15.2	14.7	18.4	16.9	15.7	14.7
		25000	18.1	16.7	15.7	15.3	19.2	17.4	16.1	15.2
		3000	14.8	13.8	12.9	12.7	15.4	14.1	13.2	12.4
6	500	15000	16.5	15.3	14.4	14.1	17.1	15.8	14.6	13.9
		25000	17.1	15.8	14.9	14.6	17.9	16.2	15.2	14.2
		3000	13.9	12.9	12.2	12.1	14.3	13	12.2	11.6
	1000	15000	15.6	14.4	13.7	13.5	16	14.7	13.8	13
		25000	16.2	14.9	14.2	14	16.7	15.3	14.2	13.4
		3000	15.3	14.1	13.7	13.1	15.9	14.5	13.7	12.9
	250	15000	16.9	15.7	14.8	14.5	17.6	16.2	15.3	14.4
		25000	17.5	16.2	15.3	15	18.4	16.7	15.7	14.7
		3000	14	13.1	12.3	12.2	14.4	13.2	12.4	11.8
8	500	15000	15.7	14.6	13.8	13.7	16.1	14.9	14	13.3
		25000	16.3	15.1	14.3	14.1	16.8	15.4	14.4	13.7
		3000	12.8	11.9	11.3	11.3	12.8	11.8	11.2	10.5
	1000	15000	14.5	13.5	12.8	12.7	14.6	13.5	12.6	12
		25000	15.2	14	13.4	18.2	15.4	14	13.2	12.3
		3000	14.6	13.6	12.8	12.7	15.2	13.9	13.1	12.4
	250	15000	16.3	15.2	14.4	14.1	16.9	15.6	14.6	13.9
		25000	16.9	15.7	14.8	14.6	17.6	16.1	15.2	14.3
		3000	13.3	12.3	11.7	11.7	13.4	12.2	11.6	11.1
10	500	15000	14.9	13.9	13.2	13.1	15.2	14	13.2	12.4
		25000	15.6	14.4	13.8	13.6	15.9	14.5	13.7	12.8
		3000	11.7	10.8	10.3	10.4	11.4	10.4	9.9	9.4
	1000	15000	13.4	12.4	11.9	11.9	13.2	12.1	11.5	10.8
		25000	14	13	12.4	12.3	13.9	12.6	12	11.3

Table 7

Required Concrete Thickness Based on K-Composite as Determined by New Design Method

CTB Thick. (in.)	CTB Modulus (ksi)	Traffic Level (Dep./Yr.)	Dual Gear				Dual Tandem			
			Subgrade Elastic Modulus (ksi)							
			5	10	20	30	5	10	20	30
		3000	15.1	14.3	13.6	13.4	15.7	14.1	13.1	12.7
	250	15000	16.6	15.7	15.1	14.8	17.2	15.4	14.4	14
		25000	17.1	16.1	15.5	15.2	17.8	15.9	14.8	14.4
		3000	15.1	14.3	13.6	13.4	15.7	14.1	13.1	12.7
6	500	15000	16.6	15.7	15.1	14.8	17.2	15.4	14.4	14
		25000	17.1	16.1	15.5	15.2	17.8	15.9	14.8	14.4
		3000	15.1	14.3	13.6	13.4	15.7	14.1	13.1	12.7
	1000	15000	16.6	15.7	15.1	14.8	17.2	15.4	14.4	14
		25000	17.1	16.1	15.5	15.2	17.8	15.9	14.8	14.4
		3000	14.7	14	13.4	13.2	14.8	13.5	12.7	12.2
	250	15000	16.1	15.4	14.8	14.6	16.3	14.8	14	13.4
		25000	16.6	15.9	15.2	15	16.8	15.2	14.4	13.8
		3000	14.7	14	13.4	13.2	14.8	13.5	12.7	12.2
8	500	15000	16.1	15.4	14.8	14.6	16.3	14.8	14	13.4
		25000	16.6	15.9	15.2	15	16.8	15.2	14.4	13.8
		3000	14.7	14	13.4	13.2	14.8	13.5	12.7	12.2
	1000	15000	16.1	15.4	14.8	14.6	16.3	14.8	14	13.4
		25000	16.6	15.9	15.2	15	16.8	15.2	14.4	13.8
		3000	14.2	13.5	13.2	12.8	14	13	12.5	12
	250	15000	15.5	15	14.5	14.2	15.3	14.3	13.8	13.2
		25000	16	15.4	14.9	14.6	15.8	14.7	14.2	13.5
		3000	14.2	13.5	13.2	12.8	14	13	12.5	12
10	500	15000	15.5	15	14.5	14.2	15.3	14.3	13.8	13.2
		25000	16	15.4	14.9	14.6	15.8	14.7	14.2	13.5
		3000	14.2	13.5	13.2	12.8	14	13	12.5	12
	1000	15000	15.5	15	14.5	14.2	15.3	14.3	13.8	13.2
		25000	16	15.4	14.9	14.6	15.8	14.7	14.2	13.5

Table 8

Required Concrete Thickness Based on K-Composite as Determined

by Corps of Engineers Method

CTB Thick. (in.)	CTB Modulus (ksi)	Traffic Level (Dep./Yr.)	Dual Gear 5	Dual Gear 10	Dual Gear 20	Dual Gear 30	Dual Tandem 5	Dual Tandem 10	Dual Tandem 20	Dual Tandem 30
			Subgrade Elastic Modulus (ksi)							
		3000	15.2	14.4	13.2	12.5	15.8	14.4	12.5	11.3
	250	15000	16.8	15.7	14.5	13.8	17.3	15.8	13.8	12.4
		25000	17.2	16.2	15	14.2	17.8	16.3	14.2	12.8
		3000	14.9	13.9	13.1	12.5	15.3	13.7	11.8	11.3
6	500	15000	16.4	15.3	14.3	13.8	16.8	15	13	12.3
		25000	16.8	15.7	14.8	14.2	17.4	15.5	13.3	12.7
		3000	14.1	13.2	12.5	12.5	14	12.1	11.3	11.3
	1000	15000	15.5	14.6	13.8	13.8	15.3	13.4	12.3	12.3
		25000	16	15	14.2	14.2	15.8	13.8	12.7	12.7
		3000	14.9	14.1	12.7	12.5	15.3	14	11.5	11.3
	250	15000	16.4	15.5	14	13.8	16.8	15.3	12.6	12.3
		25000	16.8	16	14.4	14.2	17.4	15.8	13	12.7
		3000	14.7	13.4	12.5	12.5	14.8	12.7	11.3	11.3
8	500	15000	16.1	14.8	13.8	13.8	16.3	14	12.3	12.3
		25000	16.6	15.2	14.2	14.2	16.8	14.4	12.7	12.7
		3000	13.9	13.2	12.7	12.5	13.4	12.2	11.3	11.3
	1000	15000	15.3	14.6	14	13.8	14.8	13.4	12.3	12.3
		25000	15.8	15	14.4	14.2	15.2	13.8	12.7	12.7
		3000	14.9	14	12.5	12.5	15.3	13.5	11.5	11.3
	250	15000	16.4	15.4	13.8	13.8	16.8	14.8	12.6	12.3
		25000	16.8	15.9	14.2	14.2	17.4	15.2	13	12.7
		3000	14.7	13.4	12.5	12.5	14.8	12.7	11.3	11.3
10	500	15000	16.1	14.8	13.8	13.8	16.3	14	12.3	12.3
		25000	16.6	15.2	14.2	14.2	16.8	14.4	12.7	12.7
		3000	13.5	12.5	12.5	12.5	13	11.3	11.3	11.3
	1000	15000	15	13.8	13.8	13.8	14.3	12.4	12.4	12.4
		25000	15.4	14.2	14.2	14.2	14.7	12.8	12.8	12.8

Difference in Results

The results obtained by the new method were compared with the current FAA and CE methods by computing the difference between the required concrete slab thicknesses $(H_{conc})_{new}$ minus $(H_{conc})_{current}$. These differences are shown in Tables 10 and 11. The results indicated that the current FAA design method tends to over design the concrete slabs for the cases where E_{ctb} is equal to 1,000 ksi. On the other hand, the same method tends to underestimate the required slab thickness for an E_{ctb} of 250 ksi.

In general, the current method requires a greater concrete thickness than the newly developed method in 64 percent of the cases included in the factorial design. The same condition occurred when the concrete thicknesses were determined using the K-composite relationship developed by the CE. However, only 62 percent of the cases included in our analysis required greater concrete thickness than that recommended by the new method.

No other trends were observed in the difference between the estimated concrete slab thickness using the three different methods.

Table 9

Difference in Thickness of Concrete Slab as Determined by the New Design Method and the K-Composite Method (FAA Method)

CTB Thick. (in.)	CTB Modulus (ksi)	Traffit Level (Dep./Yr.)	Dual Gear 5	Dual Gear 10	Dual Gear 20	Dual Gear 30	Dual Tandem 5	Dual Tandem 10	Dual Tandem 20	Dual Tandem 30
			Subgrade Elastic Modulus (ksi)							
		3000	0.7	0.3	0.1	0	0.9	1.1	1	0.6
	250	15000	0.8	0.5	0.1	-0.1	1.2	1.5	1.3	0.7
		25000	1.1	0.6	0.2	0.1	1.4	1.5	1.3	0.8
		3000	-0.3	-0.5	-0.7	-0.7	-0.3	0	0.1	-0.3
6	500	15000	-0.1	-0.4	-0.7	-0.7	-0.1	0.4	0.2	-0.1
		25000	0.1	-0.3	-0.6	-0.6	0.1	0.3	0.4	-0.2
		3000	-1.2	-1.4	-1.4	-1.3	-1.4	-1.1	-0.9	-1.1
	1000	15000	-1	-1.3	-1.4	-1.3	-1.2	-0.7	-0.6	-1
		25000	-0.8	-1.2	-1.3	-1.2	-1.1	-0.6	-0.6	-1
		3000	0.6	0.1	0.3	-0.1	1.1	1	1	0.7
	250	15000	0.8	0.3	0	-0.1	1.3	1.4	1.3	1
		25000	0.9	0.3	0.1	0	1.6	1.5	1.3	0.9
		3000	-0.7	-0.9	-1.1	-1	-0.4	-0.3	-0.3	-0.4
8	500	15000	-0.4	-0.8	-1	-0.9	-0.2	0.1	0	-0.1
		25000	-0.3	-0.8	-0.9	-0.9	0	0.2	0	-0.1
		3000	-1.9	-2.1	-2.1	-1.9	-2	-1.7	-1.5	-1.7
	1000	15000	-1.6	-1.9	-2	-1.9	-1.7	-1.3	-1.4	-1.4
		25000	-1.4	-1.9	-1.8	3.2	-1.4	-1.2	-1.2	-1.5
		3000	0.4	0.1	-0.4	-0.1	1.2	0.9	0.6	0.4
	250	15000	0.8	0.2	-0.1	-0.1	1.6	1.3	0.8	0.7
		25000	0.9	0.3	-0.1	0	1.8	1.4	1	0.8
		3000	-0.9	-1.2	-1.5	-1.1	-0.6	-0.8	-0.9	-0.9
10	500	15000	-0.6	-1.1	-1.3	-1.1	-0.1	-0.3	-0.6	-0.8
		25000	-0.4	-1	-1.1	-1	0.1	-0.2	-0.5	-0.7
		3000	-2.5	-2.7	-2.9	-2.4	-2.6	-2.6	-2.6	-2.6
	1000	15000	-2.1	-2.6	-2.6	-2.3	-2.1	-2.2	-2.3	-2.4
		25000	-2	-2.4	-2.5	-2.3	-1.9	-2.1	-2.2	-2.2

Table 10

Difference in Thickness of Concrete Slab as Determined by the New Design Method and the K-Composite Method (Corps of Engineers Method)

CTB Thick. (in.)	CTB Modulus (ksi)	Traffic Level (Dep./Yr.)	Dual Gear, Subgrade Elastic Modulus (ksi): 5	10	20	30	Dual Tandem, Subgrade Elastic Modulus (ksi): 5	10	20	30
		3000	0.6	0.2	0.5	0.9	0.8	0.8	1.6	2
	250	15000	0.6	0.5	0.7	0.9	1.1	1.1	1.9	2.3
		25000	0.9	0.5	0.7	1.1	1.4	1.1	1.9	2.4
		3000	-0.1	-0.1	-0.2	0.2	0.1	0.4	1.4	1.1
6	500	15000	0.1	0	0.1	0.3	0.3	0.8	1.6	1.6
		25000	0.3	0.1	0.1	0.4	0.5	0.7	1.9	1.5
		3000	-0.2	-0.3	-0.3	-0.4	0.3	0.9	0.9	0.3
	1000	15000	0.1	-0.2	-0.1	-0.3	0.7	1.3	1.5	0.7
		25000	0.2	-0.1	0	-0.2	0.9	1.5	1.5	0.7
		3000	0.4	0	1	0.6	0.6	0.5	2.2	1.6
	250	15000	0.5	0.2	0.8	0.7	0.8	0.9	2.7	2.1
		25000	0.7	0.2	0.9	0.8	1	0.9	2.7	2
		3000	-0.7	-0.3	-0.2	-0.3	-0.4	0.5	1.1	0.5
8	500	15000	-0.4	-0.2	0	-0.1	-0.2	0.9	1.7	1
		25000	-0.3	-0.1	0.1	-0.1	0	1	1.7	1
		3000	-1.1	-1.3	-1.4	-1.2	-0.6	-0.4	-0.1	-0.8
	1000	15000	-0.8	-1.1	-1.2	-1.1	-0.2	0.1	0.3	-0.3
		25000	-0.6	-1	-1	4	0.2	0.2	0.5	-0.4
		3000	-0.3	-0.4	0.3	0.2	-0.1	0.4	1.6	1.1
	250	15000	-0.1	-0.2	0.6	0.3	0.1	0.8	2	1.6
		25000	0.1	-0.2	0.6	0.4	0.2	0.9	2.2	1.6
		3000	-1.4	-1.1	-0.8	-0.8	-1.4	-0.5	0.3	-0.2
10	500	15000	-1.2	-0.9	-0.6	-0.7	-1.1	0	0.9	0.1
		25000	-1	-0.8	-0.4	-0.6	-0.9	0.1	1	0.1
		3000	-1.8	-1.7	-2.2	-2.1	-1.6	-0.9	-1.4	-1.9
	1000	15000	-1.6	-1.4	-1.9	-1.9	-1.1	-0.3	-0.9	-1.6
		25000	-1.4	-1.2	-1.8	-1.9	-0.8	-0.2	-0.8	-1.5

CLOSURE

Summary

This study has resulted in the development of a design procedure for the determination of the thickness of a cement stabilized base under a rigid pavement system. The procedure has been developed based on an equivalent interior stress criteria. Allowance has been made for the determination of the allowable pass level on the CTB material.

Two computer programs have been developed in conjunction with the study. The first program CTBDES is the design program to be utilized in the thickness determination for new pavement structures. The second CTBEVAL is an evaluation program which can be used in checking designs performed by other methods, or it can be used in an evaluation of an existing airfield.

The procedures have been developed using elastic layer analysis in the form of the BISAR program. The method has been structured around the existing FAA design procedures and is completely compatible with the current design procedures. The comparison of the new design procedures to the existing methods show that the thickness differences are both plus and minus. However, there are several cases in which the new procedure shows a substantial reduction in the required thickness of concrete. These cases occur primarily when a CTB mixture of high elastic properties are utilized in the design process. The opposite is also true. When low materials properties are used the new design requires up to 2 in. of more concrete. This is a significant finding. If the present design methods are used without consideration for the strength of the CTB material, substantial under-designs are possible.

From a design point of view the benefit to this analysis procedure is that the designer is allowed to utilize the materials properties of the CTB. In areas where CTB is a common construction material or for large projects, the reductions in concrete thickness and replacement with a higher quality CTB may provide an opportunity for economic savings. Also, the designer is provided with information regarding the allowable pass level on the CTB material. This information is not presently provided in any conventional design method.

Recommendations for Further Study

The major area encountered in this study which requires further research is the fatigue properties of the CTB materials. The literature is very sparse concerning this aspect of the material. For the most part references are made to compressive or tensile strengths; however, no major studies have been performed on the fatigue properties. There is ample work performed on lean concrete, but the strength levels of these materials are generally above the CTB materials in the 250 to 500 psi level.

It is recommended that a study of the CTB fatigue properties be undertaken to further augment this study. As an alternate, the pavements studied in the "high traffic volume" study should be continually monitored for their field performance. These pavement systems are Portland Cement Concrete (PCC) over CTB systems where the traffic and materials properties have been defined. The field performance of these pavements could be incorporated into this process through the use of the CTBEVAL program and a correlation with the Pavement Condition Index (PCI) or linear feet of cracking parameter.

This study has shown that the stress values in a three layer system are predictable. It is recommended that the methodology be extended to cover the design of other base materials such as bituminous stabilized materials.

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APPENDIX A

RESULTS OF THE STRESS ANALYSIS

Table A1

Results of Single Wheel Stress Analysis (5k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
8.0	4.0	624.0	59.5	582.0	101.0	535.0	166.0	469.0	308.0
	8.0	526.0	62.6	457.0	103.0	385.0	162.0	286.0	281.0
	10.0	483.0	60.3	405.0	96.6	326.0	149.0	223.0	245.0
	14.0	412.0	52.5	326.0	80.2	245.0	117.0	149.0	177.0
	22.0	330.0	36.5	248.0	51.6	175.0	69.4	98.0	94.8
10.0	4.0	455.0	40.2	430.0	69.2	399.0	114.0	357.0	213.0
	8.0	401.0	43.0	357.0	71.9	311.0	115.0	247.0	207.0
	10.0	375.0	42.2	325.0	69.3	273.0	109.0	203.0	189.0
	14.0	330.0	38.4	273.0	60.5	216.0	91.1	144.0	146.0
	22.0	271.0	28.7	212.0	42.1	158.0	58.8	96.2	84.5
14.0	4.0	271.0	21.9	258.0	38.2	243.0	63.8	221.0	119.0
	8.0	248.0	23.5	228.0	40.2	204.0	65.9	172.0	121.0
	10.0	237.0	23.5	213.0	39.7	187.0	64.2	151.0	116.0
	14.0	217.0	22.4	188.0	36.8	157.0	57.7	117.0	99.1
	22.0	186.0	18.6	152.0	28.7	120.0	42.2	80.7	65.7
22.0	4.0	123.0	9.2	119.0	16.5	113.0	28.1	104.0	52.9
	8.0	116.0	9.9	110.0	17.4	101.0	29.0	88.4	53.8
	10.0	113.0	10.0	105.0	17.4	95.2	28.9	81.3	53.2
	14.0	107.0	9.9	96.7	17.0	84.9	27.6	68.8	49.8
	22.0	96.6	9.1	83.0	14.9	69.1	23.2	51.2	39.4
26.0	4.0	89.6	6.7	87.1	12.0	83.5	20.6	77.2	39.0
	8.0	85.8	7.1	81.3	12.5	75.5	21.1	66.7	39.2
	10.0	83.9	7.2	78.5	12.6	71.7	21.1	62.0	39.0
	14.0	80.1	7.2	73.1	12.5	64.9	20.5	53.6	37.3
	22.0	73.2	6.8	63.9	11.3	54.0	17.9	41.2	31.0

Table A2

Results of Single Wheel Stress Analysis ([illegible]k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.	CTB	250 STRC	250 STRB	500 STRC	500 STRB	1,000 STRC	1,000 STRB	2,500 STRC	2,500 STRB
	4.0	561.0	50.5	528.0	86.7	491.0	144.0	438.0	274.0
	8.0	484.0	53.4	426.0	89.6	364.0	145.0	275.0	258.0
8.0	10.0	448.0	51.7	382.0	84.9	312.0	134.0	217.0	226.0
	14.0	391.0	45.3	314.0	71.4	239.0	106.0	148.0	165.0
	22.0	322.0	32.0	245.0	46.6	175.0	64.2	99.3	89.2
	4.0	413.0	34.5	393.0	59.9	369.0	99.7	334.0	189.0
	8.0	369.0	37.0	333.0	63.0	294.0	103.0	237.0	190.0
10.0	10.0	348.0	36.3	306.0	6[illegible].0	261.0	98.3	197.0	174.0
	14.0	312.0	33.2	261.0	53.8	210.0	83.1	143.0	136.0
	22.0	263.0	25.1	212.0	42.1	158.0	58.8	96.2	84.5
	4.0	248.0	19.1	238.0	33.6	226.0	56.4	208.0	107.0
	8.0	230.0	20.5	213.0	35.6	193.0	59.2	165.0	111.0
14.0	10.0	221.0	20.5	200.0	35.3	178.0	58.1	146.0	107.0
	14.0	204.0	19.6	179.0	32.8	152.0	52.7	115.0	92.6
	22.0	178.0	16.2	148.0	25.8	118.0	39.0	80.4	62.0
	4.0	114.0	8.3	111.0	14.8	106.0	25.3	98.7	47.9
	8.0	109.0	8.8	103.0	15.6	95.5	26.3	84.7	49.6
22.0	10.0	106.0	8.9	99.0	15.7	90.5	26.3	78.3	49.3
	14.0	101.0	8.8	91.8	15.3	81.3	25.3	66.8	46.6
	22.0	92.0	8.0	79.9	13.4	67.3	21.4	50.5	37.2
	4.0	83.8	6.0	81.6	10.9	78.4	18.7	73.1	35.5
	8.0	80.5	6.4	76.5	11.3	71.4	19.2	63.8	36.2
26.0	10.0	78.8	6.4	74.0	11.4	68.1	19.3	59.6	36.2
	14.0	75.5	6.4	69.3	11.3	62.1	18.8	52.0	34.9
	22.0	69.7	6.0	61.3	10.2	52.4	16.5	40.5	29.3

Table A3

Results of Single Wheel Stress Analysis (20k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.	CTB	250 STRC	250 STRB	500 STRC	500 STRB	1,000 STRC	1,000 STRB	2,500 STRC	2,500 STRB
8.0	4.0	499.0	41.3	472.0	72.0	443.0	121.0	402.0	237.0
	8.0	439.0	44.2	391.0	76.1	339.0	126.0	261.0	231.0
	10.0	412.0	42.9	355.0	72.6	295.0	117.0	209.0	204.0
	14.0	367.0	37.9	600.0	61.8	232.0	94.8	145.0	151.0
	22.0	313.0	27.1	241.0	41.0	174.0	58.0	100.0	82.6
10.0	4.0	371.0	28.7	354.0	50.4	335.0	84.9	309.0	165.0
	8.0	337.0	30.8	307.0	53.8	274.0	90.2	224.0	171.0
	10.0	320.0	30.3	285.0	52.4	246.0	86.6	189.0	158.0
	14.0	292.0	27.8	248.0	46.6	202.0	74.1	139.0	125.0
	22.0	254.0	21.2	204.0	33.4	155.0	49.1	96.9	73.8
14.0	4.0	226.0	16.2	217.0	28.8	208.0	48.7	193.0	93.6
	8.0	211.0	17.3	196.0	30.7	180.0	52.0	156.0	101.0
	10.0	204.0	17.3	186.0	30.5	167.0	51.4	139.0	97.6
	14.0	191.0	16.5	169.0	28.5	145.0	47.0	111.0	85.0
	22.0	170.0	13.7	143.0	22.6	116.0	35.2	79.8	57.5
22.0	4.0	105.0	7.2	102.0	13.0	98.4	22.3	92.3	42.5
	8.0	101.0	7.6	95.5	13.7	89.4	23.3	80.3	45.0
	10.0	98.5	7.7	92.3	13.8	85.1	23.4	74.6	45.0
	14.0	94.3	7.5	86.3	13.4	77.3	22.7	64.4	42.9
	22.0	87.0	6.8	76.4	11.8	65.1	19.4	49.5	34.6
26.0	4.0	77.6	5.3	75.6	9.6	72.9	16.5	68.5	31.6
	8.0	74.7	5.5	35.5	10.0	66.9	17.1	60.6	32.9
	10.0	73.3	5.6	69.1	10.1	64.1	17.2	56.8	33.1
	14.0	70.6	5.5	65.1	10.0	58.9	16.9	50.0	32.1
	22.0	65.8	5.1	58.4	9.0	50.5	14.9	39.5	27.3

Table A4

Results of Single Wheel Stress Analysis (30k Subgrade)

Concrete Thickness, in.		CTB Modulus, ksi							
		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
8.0	4.0	463.0	36.1	439.0	63.7	414.0	108.0	379.0	216.0
	8.0	413.0	38.8	370.0	68.1	323.0	115.0	251.0	214.0
	10.0	391.0	37.8	339.0	65.3	283.0	107.0	203.0	191.0
	14.0	353.0	33.5	291.0	55.9	226.0	87.5	144.0	142.0
	22.0	307.0	24.2	238.0	37.5	173.0	54.0	101.0	78.3
10.0	4.0	347.0	25.2	331.0	44.8	315.0	76.3	292.0	151.0
	8.0	318.0	27.2	290.0	48.3	261.0	82.4	216.0	159.0
	10.0	304.0	26.8	271.0	47.2	236.0	79.4	183.0	148.0
	14.0	280.0	24.6	240.0	42.2	197.0	68.3	137.0	117.0
	22.0	248.0	18.9	200.0	30.4	154.0	45.8	96.8	69.9
14.0	4.0	212.0	14.4	205.0	25.9	196.0	44.1	184.0	85.8
	8.0	200.0	15.5	187.0	27.8	172.0	47.7	151.0	93.8
	10.0	194.0	15.4	178.0	27.6	161.0	47.2	135.0	91.4
	14.0	183.0	14.7	162.0	25.9	141.0	43.4	109.0	80.1
	22.0	166.0	12.2	140.0	20.6	114.0	32.7	79.2	54.5
22.0	4.0	99.9	6.5	97.0	11.8	93.6	20.4	88.3	39.2
	8.0	95.9	6.9	91.1	12.5	85.5	21.5	77.5	42.0
	10.0	93.9	6.9	88.2	12.6	81.6	21.6	74.6	42.3
	14.0	90.3	6.8	82.8	12.3	74.6	21.0	64.4	40.5
	22.0	84.1	6.1	74.1	10.8	63.6	18.0	49.5	37.8
26.0	4.0	74.0	4.8	71.8	8.8	69.4	15.2	65.6	29.2
	8.0	71.2	5.0	67.9	9.2	64.1	15.8	60.6	30.8
	10.0	69.9	5.0	66.0	9.2	61.5	15.9	56.8	31.1
	14.0	67.5	5.0	62.5	9.1	56.8	15.7	50.0	30.3
	22.0	63.4	4.6	56.5	8.3	49.2	13.9	39.5	25.9

Table A5

Results of Dual-Wheel Gear Stress Analysis (5k Subgrade)

Concrete Thickness, in.		CTB Modulus, ksi							
		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
	4.0	959.0	93.7	890.0	161.0	809.0	265.0	696.0	488.0
	8.0	802.0	99.8	689.0	163.0	572.0	254.0	418.0	435.0
8.0	10.0	730.0	96.7	605.0	153.0	481.0	233.0	325.0	380.0
	14.0	614.0	85.5	480.0	129.0	356.0	185.0	215.0	280.0
	22.0	476.0	63.5	352.0	86.8	247.0	114.0	140.0	157.0
	4.0	716.0	65.1	673.0	114.0	620.0	188.0	541.0	347.0
	8.0	625.0	70.7	550.0	118.0	471.0	187.0	365.0	328.0
10.0	10.0	580.0	69.9	496.0	114.0	410.0	176.0	299.0	299.0
	14.0	503.0	64.5	408.0	100.0	318.0	148.0	209.0	234.0
	22.0	398.0	51.9	305.0	73.6	223.0	100.0	134.0	141.0
	4.0	439.0	36.7	418.0	65.2	390.0	110.0	347.0	204.0
	8.0	400.0	40.3	363.0	68.9	321.0	112.0	263.0	200.0
14.0	10.0	380.0	40.6	337.0	68.2	290.0	108.0	228.0	190.0
	14.0	343.0	39.9	291.0	63.8	239.0	98.0	173.0	164.0
	22.0	284.0	35.2	227.0	52.8	174.0	75.6	114.0	115.0
	4.0	209.0	16.3	202.0	29.6	192.0	51.1	174.0	96.4
	8.0	198.0	17.8	185.0	31.3	168.0	52.0	144.0	94.5
22.0	10.0	192.0	18.3	176.0	31.6	157.0	51.7	131.0	92.8
	14.0	180.0	18.8	160.0	31.6	138.0	50.2	109.0	87.6
	22.0	159.0	18.0	134.0	29.0	108.0	44.2	77.9	73.3
	4.0	156.0	12.1	151.0	22.2	144.0	38.5	132.0	72.7
	8.0	149.0	13.2	140.0	23.3	129.0	38.8	112.0	70.7
26.0	10.0	146.0	13.5	135.0	23.7	122.0	38.9	103.0	69.7
	14.0	138.0	13.9	125.0	23.8	109.0	38.3	87.8	67.9
	22.0	124.0	13.6	106.0	22.4	87.8	34.8	65.2	59.1

Table A6

Results of Dual-Wheel Gear Stress Analysis (10k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
	4.0	838.0	76.5	785.0	133.0	724.0	222.0	637.0	419.0
	8.0	718.0	82.0	627.0	137.0	531.0	220.0	398.0	387.0
8.0	10.0	662.0	79.8	559.0	130.0	454.0	204.0	315.0	342.0
	14.0	571.0	71.3	456.0	111.0	346.0	164.0	214.0	255.0
	22.0	460.0	54.1	347.0	76.4	248.0	103.0	143.0	145.0
	4.0	623.0	54.0	598.0	95.0	557.0	159.0	497.0	300.0
	8.0	560.0	58.8	501.0	99.8	436.0	162.0	346.0	293.0
10.0	10.0	526.0	58.2	457.0	97.1	385.0	154.0	287.0	269.0
	14.0	465.0	54.1	385.0	86.4	306.0	132.0	206.0	214.0
	22.0	382.0	44.3	297.0	64.9	221.0	90.4	136.0	131.0
	4.0	394.0	31.2	376.0	55.8	354.0	94.5	320.0	178.0
	8.0	362.0	34.2	331.0	59.3	297.0	97.7	249.0	179.0
14.0	10.0	346.0	34.4	310.0	58.9	271.0	95.6	218.0	172.0
	14.0	316.0	33.8	272.0	55.4	227.0	87.3	168.0	150.0
	22.0	269.0	30.1	218.0	46.7	170.0	68.6	113.0	107.0
	4.0	191.0	14.3	185.0	26.1	176.0	45.1	161.0	85.5
	8.0	181.0	15.6	170.0	27.6	156.0	46.3	136.0	85.5
22.0	10.0	176.0	16.0	163.0	27.9	147.0	46.2	125.0	84.5
	14.0	167.0	16.3	149.0	27.9	130.0	45.1	105.0	80.6
	22.0	149.0	15.7	127.0	25.8	104.0	40.3	76.4	68.5
	4.0	144.0	10.7	139.0	19.8	133.0	34.3	123.0	64.9
	8.0	137.0	11.6	130.0	20.7	120.0	34.7	105.0	64.1
26.0	10.0	134.0	11.9	125.0	21.0	114.0	34.9	97.9	63.6
	14.0	128.0	12.2	116.0	21.2	103.0	34.6	84.3	62.5
	22.0	116.0	11.9	101.0	20.0	84.2	31.8	63.6	55.3

Table A7

Results of Dual-Wheel Gear Stress Analysis (20k Subgrade)

Concrete Thickness, in.		CTB Modulus, ksi							
		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
8.0	4.0	723.0	60.4	682.0	107.0	638.0	181.0	572.0	352.0
	8.0	635.0	65.2	563.0	112.0	486.0	185.0	372.0	337.0
	10.0	595.0	63.7	511.0	107.0	423.0	173.0	300.0	300.0
	14.0	527.0	57.4	429.0	92.8	332.0	142.0	211.0	227.0
	22.0	443.0	44.3	340.0	65.0	247.0	91.0	145.0	131.0
10.0	4.0	550.0	43.2	523.0	77.0	493.0	131.0	448.0	253.0
	8.0	497.0	47.2	449.0	82.1	398.0	137.0	323.0	256.0
	10.0	471.0	46.8	416.0	80.2	356.0	131.0	272.0	237.0
	14.0	426.0	43.7	359.0	72.3	290.0	114.0	200.0	191.0
	22.0	363.0	36.3	288.0	55.3	218.0	79.5	137.0	119.0
14.0	4.0	347.0	25.6	333.0	46.2	316.0	78.9	291.0	151.0
	8.0	323.0	27.9	298.0	49.5	271.0	83.1	232.0	157.0
	10.0	311.0	28.1	281.0	49.3	250.0	82.0	205.0	153.0
	14.0	288.0	27.5	252.0	46.7	214.0	75.7	162.0	135.0
	22.0	252.0	24.9	208.0	39.9	165.0	60.6	112.0	97.1
22.0	4.0	172.0	12.1	167.0	22.3	159.0	38.7	148.0	74.0
	8.0	164.0	13.1	155.0	23.6	143.0	40.1	127.0	75.6
	10.0	160.0	13.4	149.0	23.8	136.0	40.2	117.0	75.4
	14.0	152.0	13.7	138.0	24.0	122.0	39.5	99.8	72.6
	22.0	138.0	13.1	119.0	22.4	99.6	35.9	74.3	62.8
26.0	4.0	130.0	9.2	126.0	17.1	121.0	29.7	113.0	56.6
	8.0	125.0	9.9	118.0	17.9	110.0	30.2	98.4	57.0
	10.0	122.0	10.1	115.0	18.2	105.0	30.5	91.9	56.9
	14.0	117.0	10.4	107.0	18.3	95.7	30.6	80.1	56.6
	22.0	108.0	10.1	94.3	17.4	80.1	28.4	61.6	50.8

Table A8

Results of Dual-Wheel Gear Stress Analysis (30k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
8.0	4.0	659.0	51.6	625.0	92.2	587.0	158.0	532.0	314.0
	8.0	589.0	56.0	526.0	98.2	457.0	165.0	355.0	306.0
	10.0	556.0	54.9	482.0	94.5	402.0	155.0	290.0	275.0
	14.0	502.0	49.7	413.0	82.2	322.0	128.0	208.0	210.0
	22.0	432.0	38.6	335.0	58.0	246.0	83.3	146.0	123.0
10.0	4.0	505.0	37.2	481.0	67.0	455.0	115.0	418.0	226.0
	8.0	461.0	40.7	419.0	72.1	374.0	122.0	308.0	233.0
	10.0	440.0	40.4	391.0	70.7	338.0	118.0	261.0	217.0
	14.0	404.0	37.8	343.0	64.1	280.0	103.0	196.0	176.0
	22.0	351.0	31.7	282.0	49.5	251.0	72.6	137.0	111.0
14.0	4.0	321.0	22.3	308.0	40.6	294.0	69.9	272.0	136.0
	8.0	300.0	24.4	279.0	43.8	255.0	74.0	220.0	144.0
	10.0	290.0	24.5	264.0	43.7	236.0	73.8	196.0	140.0
	14.0	272.0	23.9	239.0	41.5	205.0	68.6	157.0	119.0
	22.0	242.0	21.8	201.0	35.8	162.0	55.5	111.0	90.8
22.0	4.0	161.0	10.7	156.0	19.9	149.0	34.8	139.0	67.0
	8.0	154.0	11.6	145.0	21.1	135.0	36.3	121.0	69.5
	10.0	150.0	11.9	140.0	21.4	128.0	36.5	112.0	69.6
	14.0	144.0	12.1	130.0	21.5	116.0	36.0	96.3	67.5
	22.0	132.0	11.6	114.0	20.2	96.4	33.0	72.7	59.0
26.0	4.0	122.0	8.2	119.0	15.4	114.0	26.8	107.0	51.5
	8.0	117.0	8.8	111.0	16.1	104.0	27.5	93.8	52.5
	10.0	115.0	9.0	108.0	16.4	99.8	27.8	88.0	52.7
	14.0	111.0	9.2	102.0	16.6	91.3	28.0	77.2	52.8
	22.0	103.0	9.0	90.4	15.8	77.3	26.2	60.1	47.9

Table A9

Results of Dual-Tandem Gear Stress Analysis (5k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
	4.0	685.0	69.6	637.0	123.0	578.0	208.0	492.0	389.0
	8.0	578.0	77.9	497.0	130.0	408.0	205.0	289.0	351.0
8.0	10.0	528.0	77.1	437.0	125.0	342.0	191.0	221.0	312.0
	14.0	445.0	70.6	345.0	108.0	249.0	156.0	140.0	238.0
	22.0	343.0	53.7	248.0	75.2	167.0	101.0	84.7	143.0
	4.0	543.0	51.9	510.0	93.1	466.0	158.0	398.0	296.0
	8.0	474.0	58.9	415.0	99.8	348.0	160.0	261.0	278.0
10.0	10.0	439.0	59.4	371.0	97.6	301.0	151.0	210.0	254.0
	14.0	377.0	56.4	302.0	87.8	229.0	129.0	143.0	204.0
	22.0	293.0	47.6	220.0	65.3	155.0	89.5	86.9	130.0
	4.0	365.0	32.3	347.0	59.1	321.0	102.0	277.0	193.0
	8.0	331.0	36.8	297.0	64.1	257.0	104.0	201.0	184.0
14.0	10.0	314.0	38.2	274.0	64.0	229.0	102.0	171.0	174.0
	14.0	279.0	39.0	231.0	60.7	183.0	91.9	126.0	150.0
	22.0	222.0	36.2	172.0	51.8	128.0	70.4	78.7	106.0
	4.0	194.0	16.2	187.0	30.9	176.0	55.1	156.0	105.0
	8.0	183.0	18.7	169.0	33.3	151.0	54.7	123.0	94.2
20.0	10.0	177.0	19.5	161.0	33.8	140.0	54.7	110.0	94.6
	14.0	165.0	20.5	143.0	34.0	119.0	52.1	88.1	87.1
	22.0	141.0	20.7	114.0	32.2	87.6	46.7	59.0	72.8
	4.0	150.0	12.5	145.0	23.9	138.0	43.1	123.0	83.4
	8.0	143.0	14.2	134.0	25.6	121.0	42.9	99.9	76.0
26.0	10.0	139.0	14.8	128.0	26.1	113.0	42.5	90.4	73.9
	14.0	131.0	15.6	116.0	26.5	97.9	41.5	74.3	69.0
	22.0	115.0	16.1	95.0	25.7	74.6	38.3	51.4	61.3

Table A10

Results of Dual-Tandem Gear Stress Analysis (10k Subgrade)

CTB Modulus ,ksi

Concrete Thickness, in.	CTB	250 STRC	250 STRB	500 STRC	500 STRB	1,000 STRC	1,000 STRB	2,500 STRC	2,500 STRB
	4.0	569.0	52.4	537.0	94.1	498.0	162.0	437.0	313.0
	8.0	496.0	59.1	436.0	102.0	369.0	166.0	270.0	296.0
8.0	10.0	461.0	58.7	391.0	98.6	315.0	156.0	212.0	265.0
	14.0	402.0	54.5	321.0	86.8	239.0	130.0	141.0	206.0
	22.0	326.0	42.5	244.0	62.4	169.0	87.0	89.5	127.0
	4.0	449.0	39.7	426.0	72.0	396.0	124.0	350.0	239.0
	8.0	401.0	45.1	358.0	78.7	311.0	130.0	241.0	234.0
10.0	10.0	377.0	45.5	328.0	77.5	273.0	124.0	198.0	217.0
	14.0	335.0	43.7	276.0	70.9	216.0	108.0	140.0	177.0
	22.0	274.0	37.2	212.0	54.2	154.0	77.0	89.4	115.0
	4.0	307.0	25.5	294.0	47.1	275.0	82.4	243.0	158.0
	8.0	282.0	29.1	257.0	51.6	226.0	86.0	183.0	156.0
14.0	10.0	269.0	29.8	239.0	51.8	204.0	84.4	158.0	150.0
	14.0	244.0	30.5	207.0	49.6	169.0	77.6	120.0	131.0
	22.0	202.0	29.1	161.0	27.5	123.0	60.5	78.4	94.4
	4.0	169.0	13.3	163.0	20.3	154.0	46.1	138.0	88.2
	8.0	160.0	15.3	149.0	21.8	134.0	46.1	112.0	80.4
22.0	10.0	155.0	16.0	142.0	22.2	125.0	46.0	101.0	82.6
	14.0	145.0	16.9	128.0	22.6	108.0	44.6	82.3	77.0
	22.0	126.0	17.3	104.0	22.3	82.1	40.9	56.9	65.5
	4.0	132.0	10.5	128.0	16.5	122.0	36.8	110.0	71.5
	8.0	126.0	11.9	118.0	17.7	108.0	36.7	90.9	66.3
26.0	10.0	123.0	12.4	113.0	18.1	101.0	36.5	83.0	64.9
	14.0	116.0	13.1	104.0	18.5	89.1	35.9	69.2	61.3
	22.0	103.0	13.6	86.7	18.5	69.5	33.8	49.2	55.4

Table A11

Results of Dual-Tandem Gear Stress Analysis (20k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
	4.0	479.0	38.9	456.0	70.6	429.0	123.0	386.0	247.0
	8.0	428.0	43.4	383.0	77.7	331.0	131.0	250.0	244.0
8.0	10.0	404.0	43.3	350.0	75.7	289.0	125.0	201.0	221.0
	14.0	363.0	40.3	297.0	67.4	228.0	105.0	139.0	173.0
	22.0	310.0	32.1	238.0	49.6	169.0	72.7	93.7	109.0
	4.0	373.0	29.1	356.0	53.8	337.0	94.6	306.0	188.0
	8.0	340.0	33.2	310.0	59.9	275.0	102.0	220.0	192.0
10.0	10.0	325.0	33.5	288.0	59.4	246.0	99.0	185.0	180.0
	14.0	296.0	32.4	250.0	55.0	201.0	87.5	135.0	149.0
	22.0	255.0	27.3	202.0	43.0	151.0	63.8	91.2	99.4
	4.0	254.0	19.1	244.0	36.0	231.0	63.7	209.0	125.0
	8.0	237.0	21.8	218.0	39.9	196.0	68.3	164.0	129.0
14.0	10.0	228.0	22.4	205.0	40.2	180.0	67.7	145.0	125.0
	14.0	210.0	22.5	183.0	39.0	153.0	63.1	113.0	111.0
	22.0	182.0	22.1	150.0	34.0	117.0	50.4	77.4	81.9
	4.0	143.0	10.4	139.0	20.3	132.0	36.8	120.0	71.5
	8.0	136.0	11.9	128.0	22.0	117.0	37.1	99.8	65.9
22.0	10.0	133.0	12.5	122.0	22.5	109.0	37.9	91.0	70.0
	14.0	125.0	13.2	112.0	22.9	96.3	36.9	75.6	66.2
	22.0	112.0	13.7	93.7	22.5	75.8	34.5	54.3	57.2
	4.0	113.0	8.3	110.0	16.5	105.0	30.2	95.9	59.0
	8.0	109.0	9.5	102.0	17.7	94.2	30.2	81.2	56.2
26.0	10.0	106.0	9.9	98.6	18.1	89.0	30.2	74.7	55.4
	14.0	101.0	10.5	91.2	18.5	79.4	30.0	63.4	53.1
	22.0	91.3	11.0	77.8	18.5	63.7	28.8	46.5	48.9

Table A12

Results of Dual-Tandem Gear Stress Analysis (30k Subgrade)

CTB Modulus, ksi

Concrete Thickness, in.		250		500		1,000		2,500	
	CTB	STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
	4.0	436.0	32.6	416.0	59.9	394.0	106.0	358.0	217.0
	8.0	395.0	36.3	356.0	66.3	310.0	114.0	238.0	217.0
8.0	10.0	376.0	36.0	328.0	64.6	274.0	109.0	193.0	197.0
	14.0	343.0	33.3	284.0	57.6	221.0	92.2	138.0	154.0
	22.0	301.0	26.5	234.0	42.4	169.0	63.3	95.7	98.2
	4.0	336.0	23.9	323.0	44.8	307.0	79.8	282.0	162.0
	8.0	311.0	27.2	285.0	50.3	255.0	87.5	207.0	169.0
10.0	10.0	298.0	27.5	267.0	50.0	231.0	85.1	176.0	159.0
	14.0	276.0	26.5	236.0	46.5	193.0	76.0	132.0	133.0
	22.0	244.0	22.6	197.0	36.7	149.0	56.1	91.8	89.7
	4.0	226.0	15.7	218.0	30.1	207.0	53.8	191.0	108.0
	8.0	212.0	18.0	197.0	33.6	180.0	57.4	153.0	113.0
14.0	10.0	205.0	18.4	187.0	33.9	167.0	58.3	136.0	110.0
	14.0	193.0	18.5	170.0	33.0	144.0	54.9	108.0	99.1
	22.0	171.0	18.2	143.0	28.7	114.0	44.4	76.5	74.1
	4.0	129.0	8.7	125.0	17.1	119.0	31.3	109.0	62.4
	8.0	123.0	9.9	116.0	18.6	106.0	31.7	92.2	57.2
22.0	10.0	120.0	10.4	111.0	19.1	100.0	32.2	84.6	62.5
	14.0	114.0	11.1	102.0	19.6	89.2	32.4	71.2	59.6
	22.0	103.0	11.6	87.4	19.6	71.8	30.6	52.5	52.0
	4.0	103.0	6.9	99.6	14.1	95.3	26.1	87.7	51.6
	8.0	98.6	8.0	93.1	15.2	86.1	26.3	75.1	50.1
26.0	10.0	96.5	8.4	89.9	15.6	81.7	26.4	69.5	49.7
	14.0	92.4	9.0	83.6	16.0	73.5	26.3	59.6	48.0
	22.0	84.3	9.4	72.4	16.2	60.0	25.8	44.7	44.6

APPENDIX B

ILLUSTRATION OF RELATIONSHIPS BETWEEN THE VARIABLES INCLUDED IN THE FACTORIAL

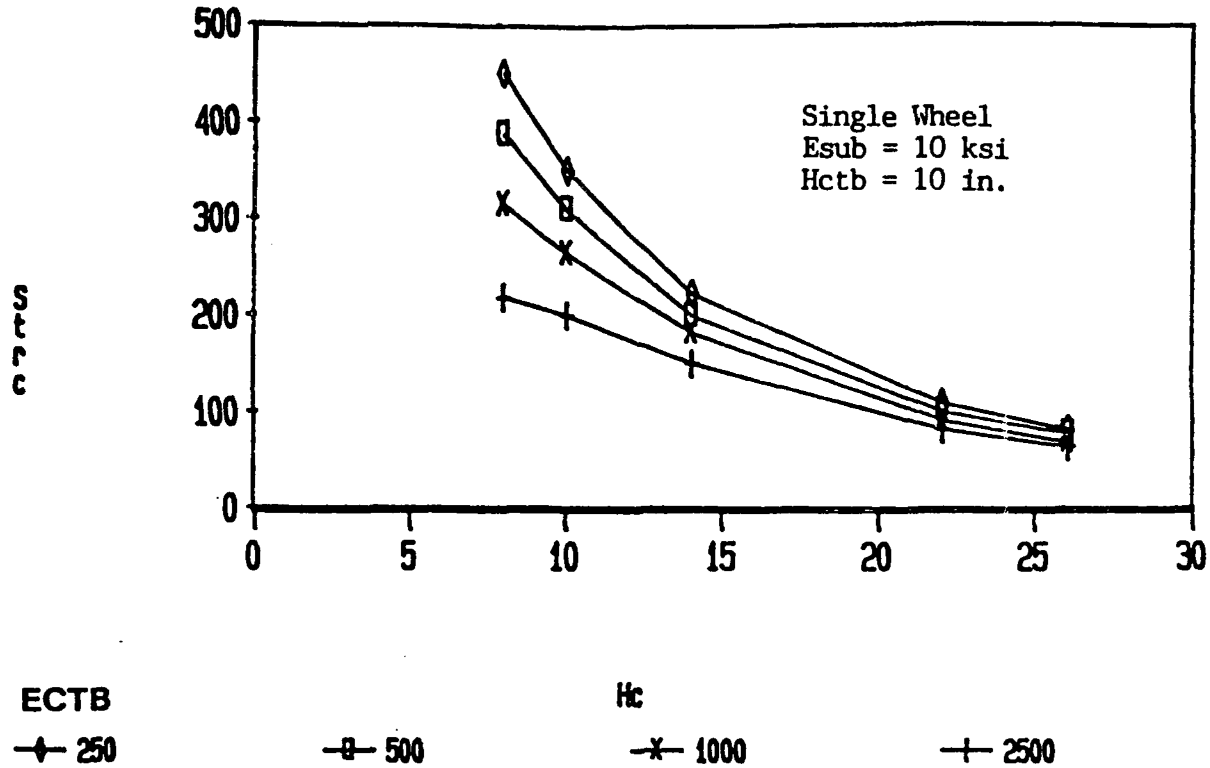

Figure B1. Relationship between Hc and stress in the concrete slab for all CTB moduli

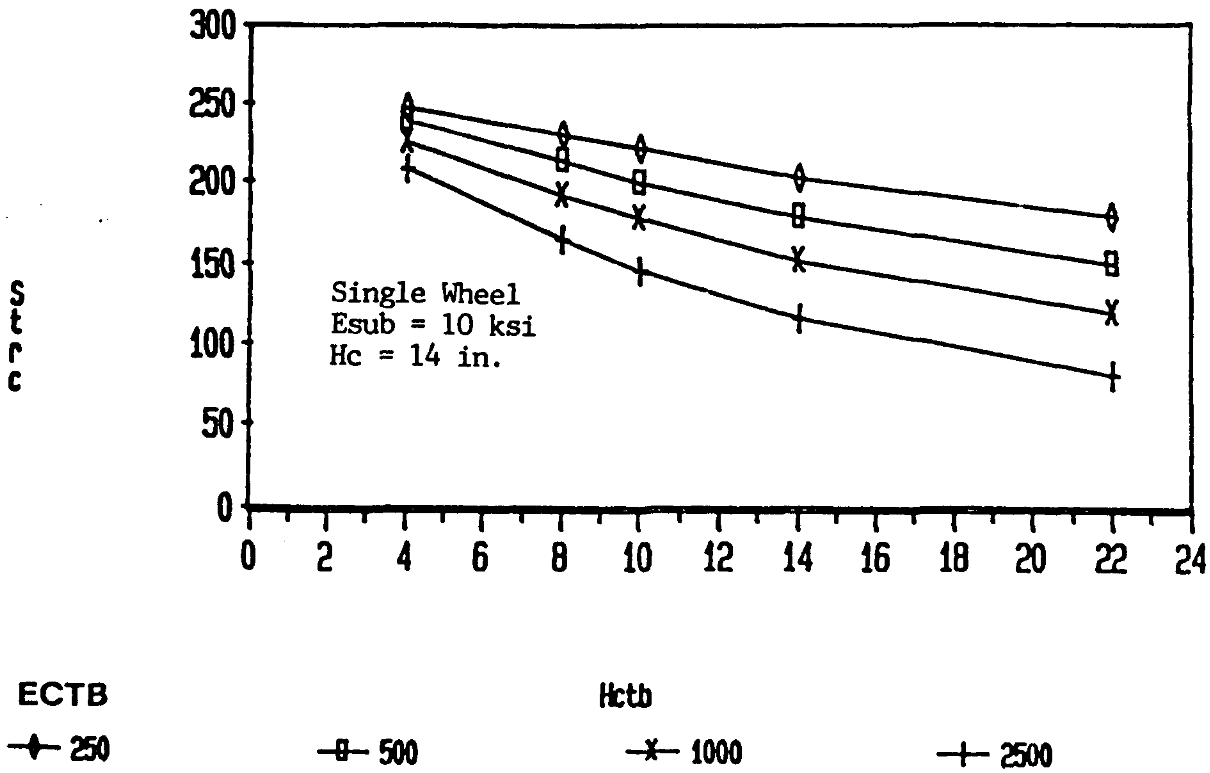

Figure B2. Relationship between Hctb and stress in the concrete slab for all CTB moduli

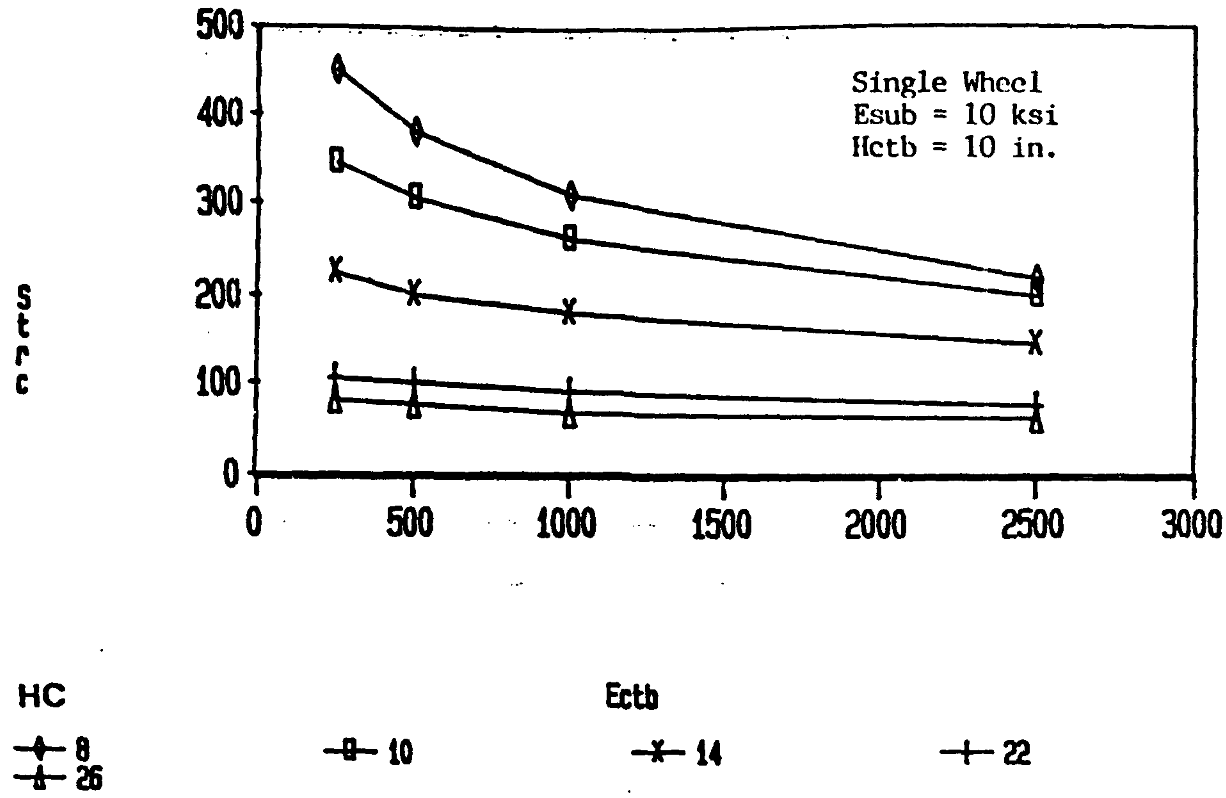

Figure B3. Relationship between Ectb and stress in the concrete slab for all concrete thicknesses

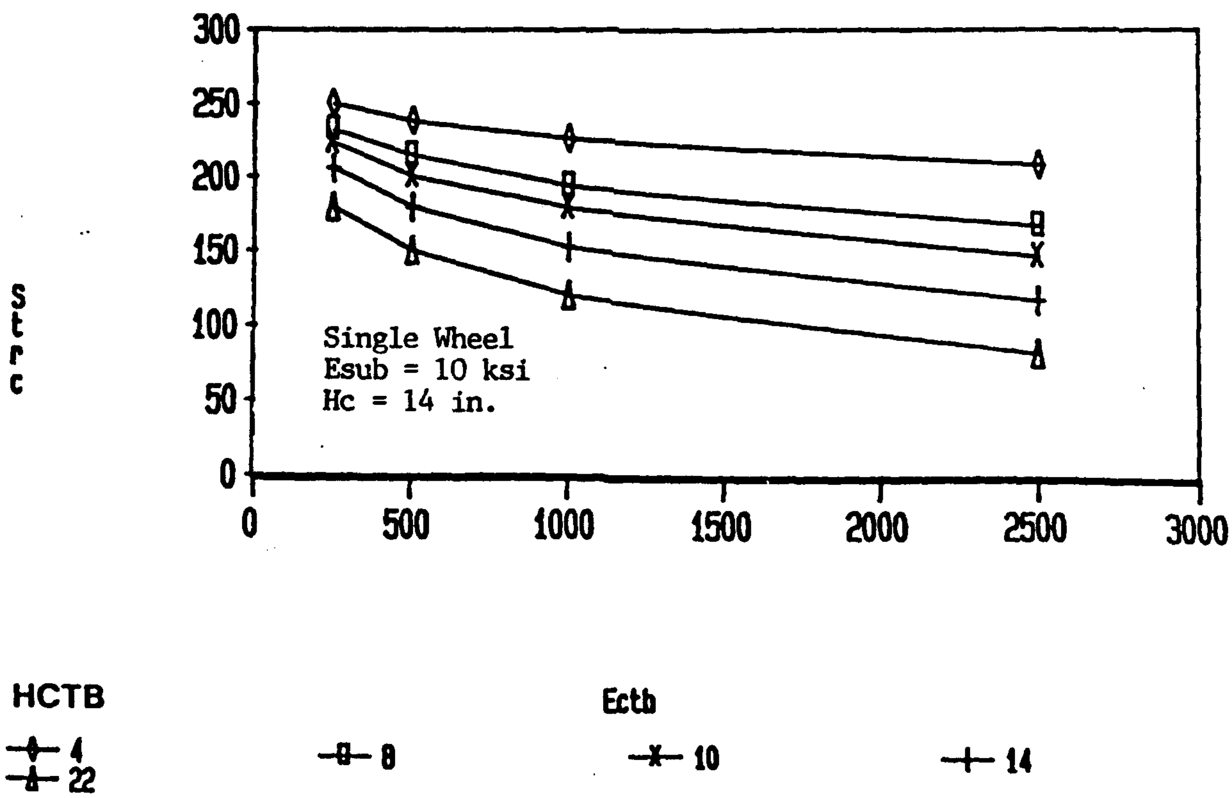

Figure B4. Relationship between Ectb and stress in the concrete slab for all CTB thicknesses

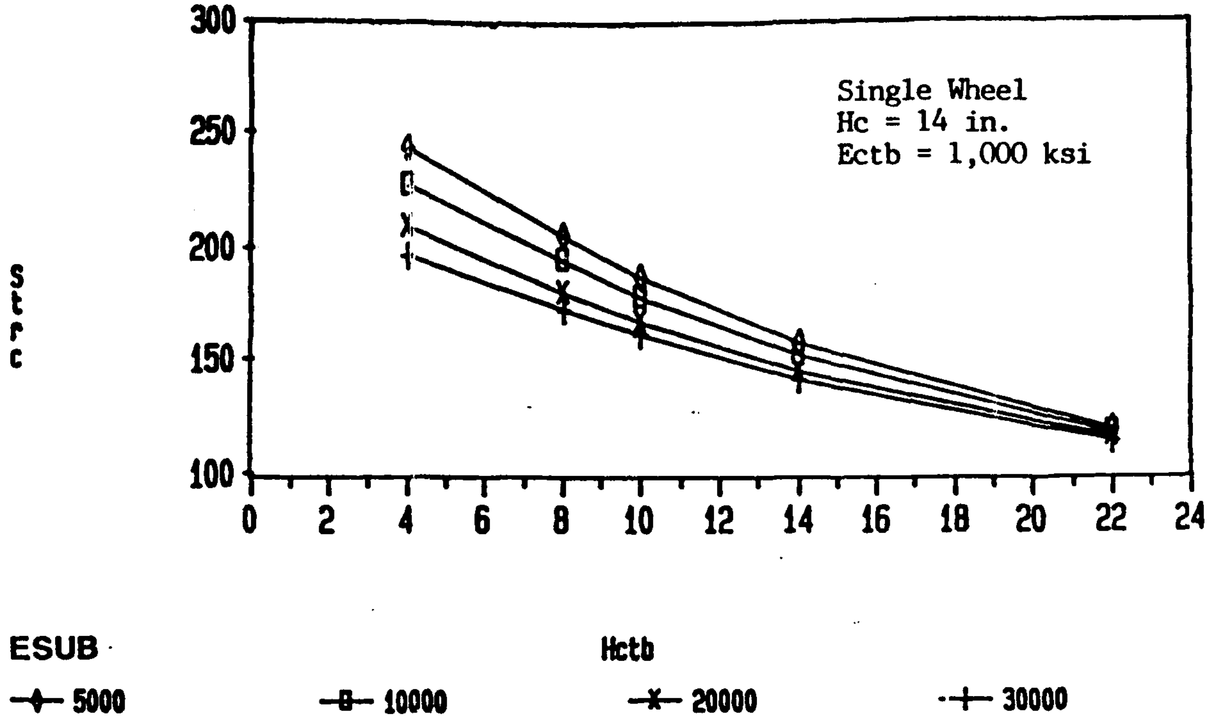

Figure B5. Relationship between Hctb and stress in the concrete slab for all subgrade moduli

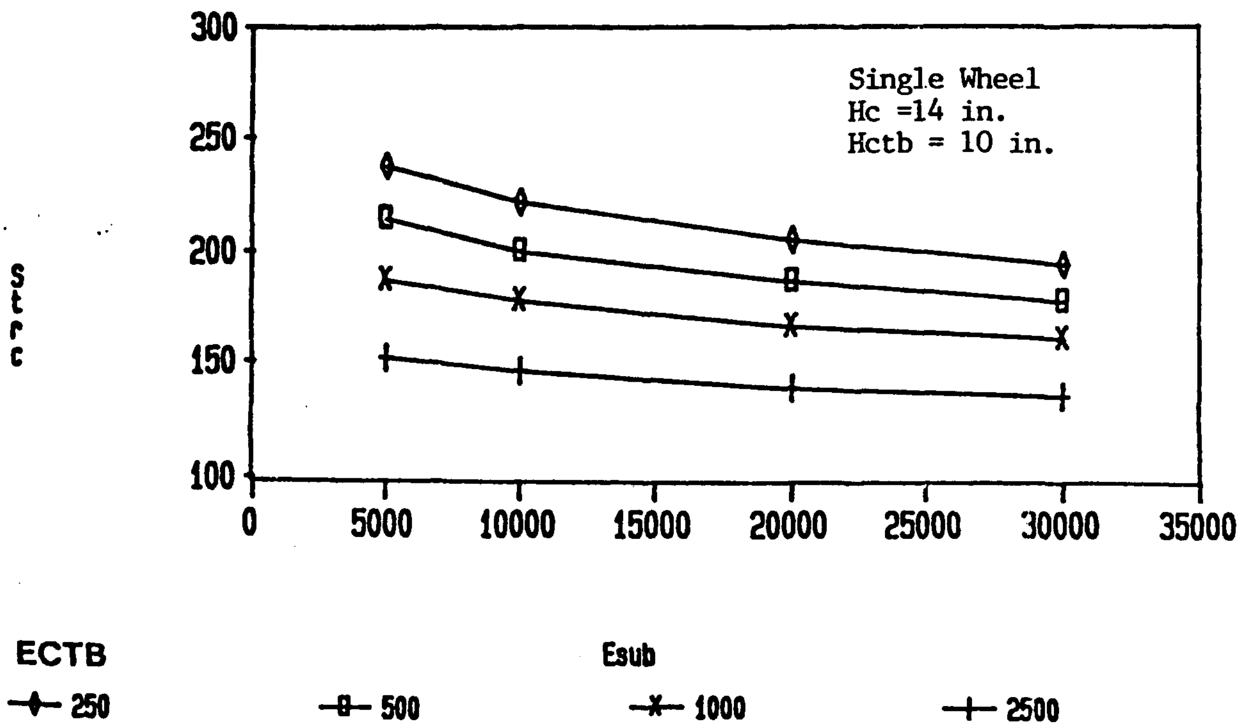

Figure B6. Relationship between Esub and stress in the concrete slab for all CTB moduli

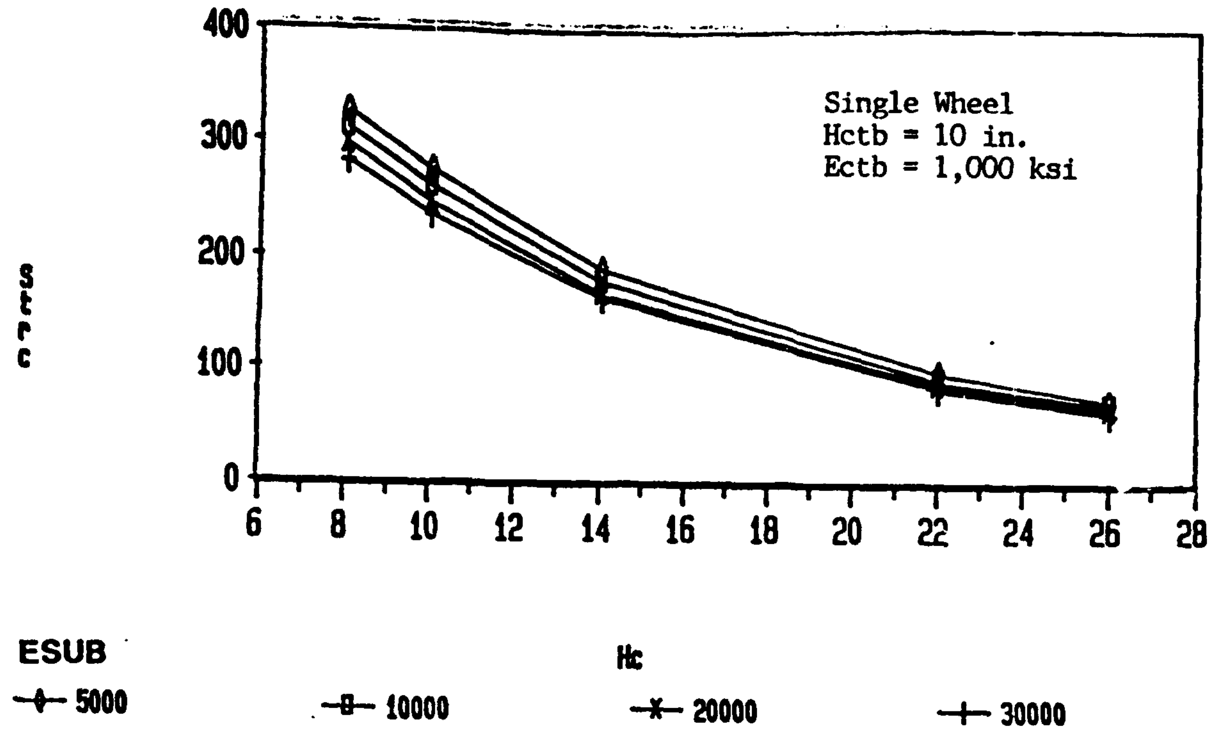

Figure B7. Relationship between Hc and stress in the concrete slab for all subgrade moduli

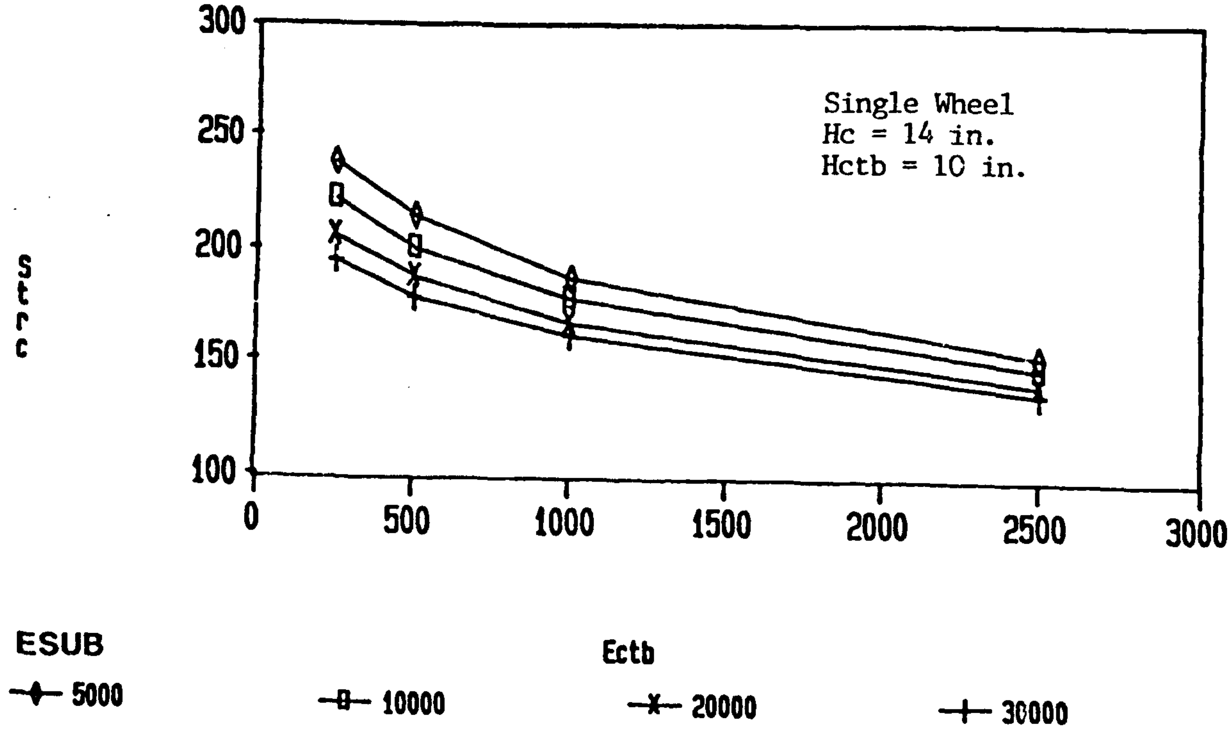

Figure B8. Relationship between Ectb and stress in the concrete slab for all subgrade moduli

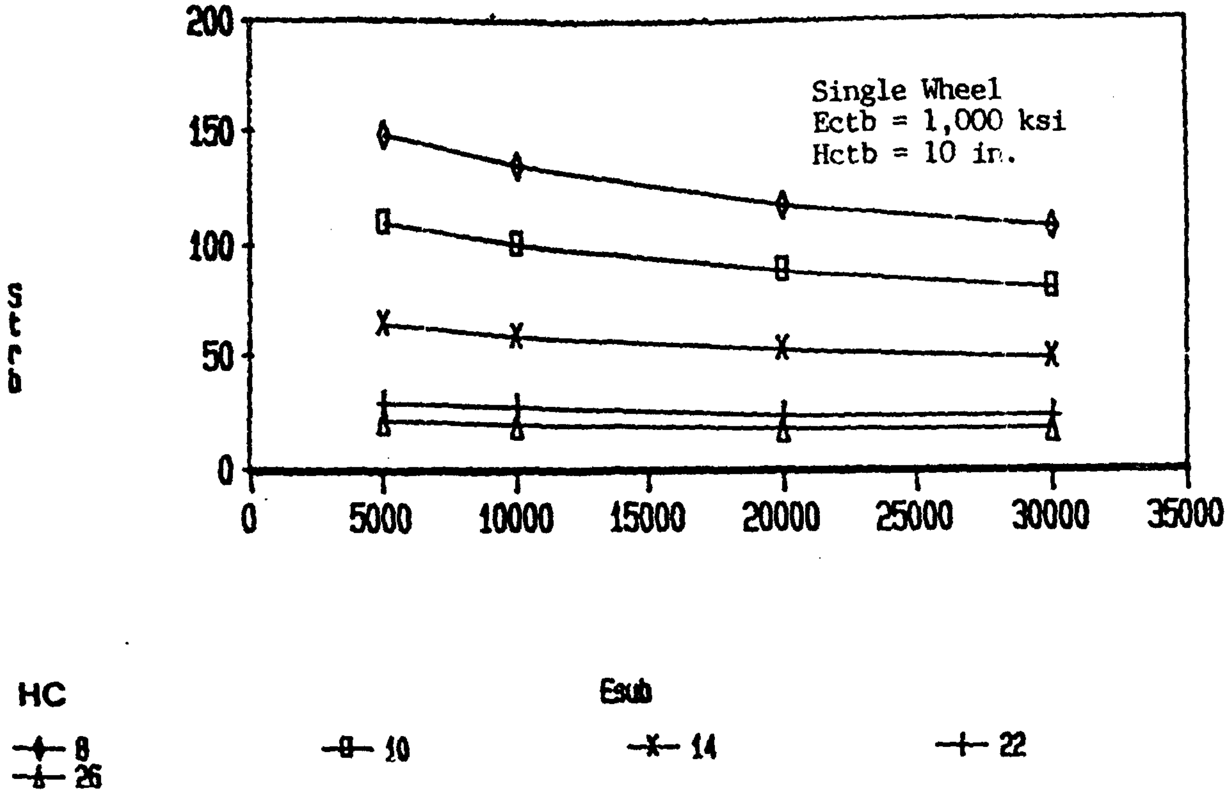

Figure B9. Relationship between Esub and stress in the CTB for all concrete slab thicknesses

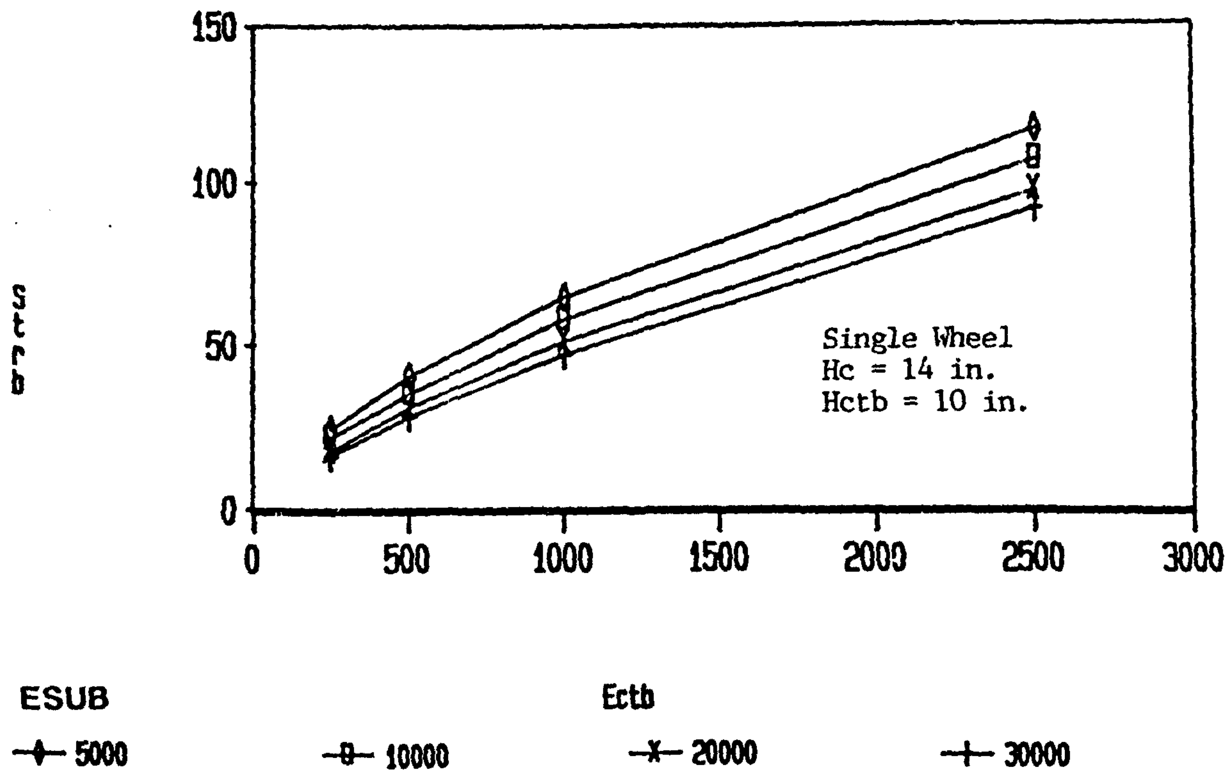

Figure B10. Relationship between Ectb and stress in the CTB for all subgrade moduli

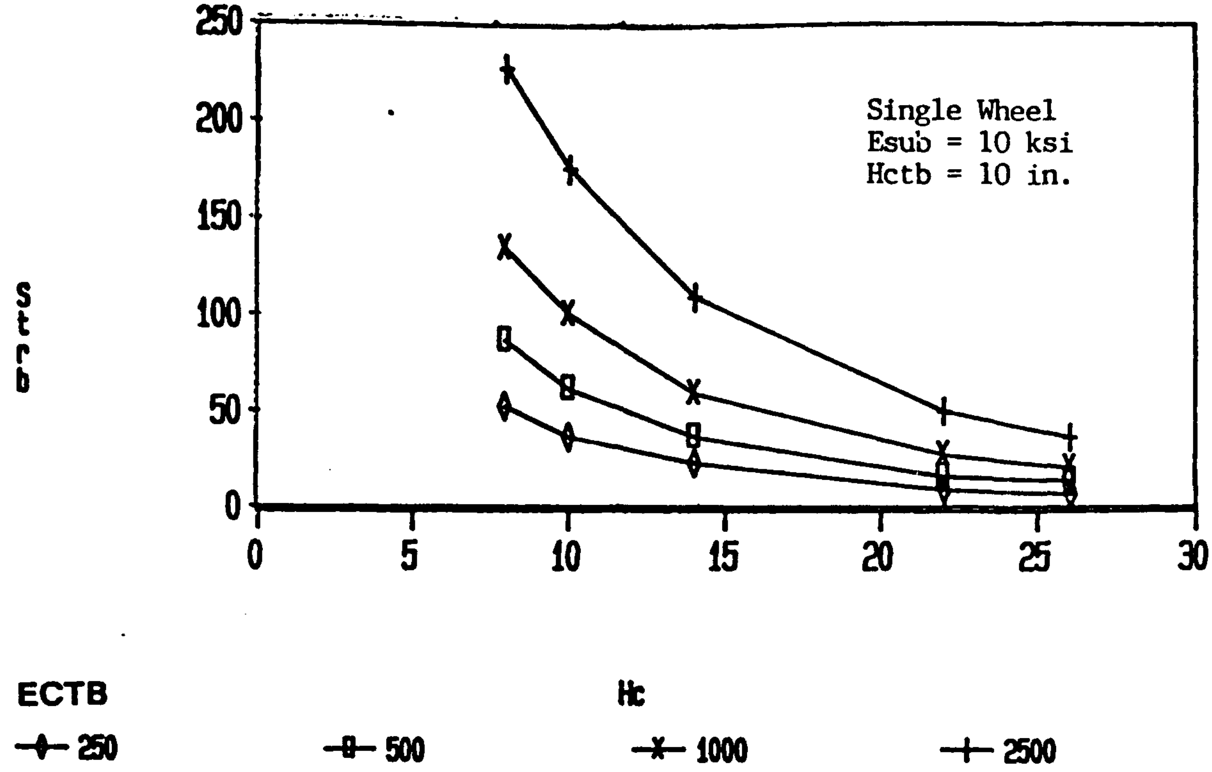

Figure B11. Relationship between Hc and stress in the CTB for all CTB moduli

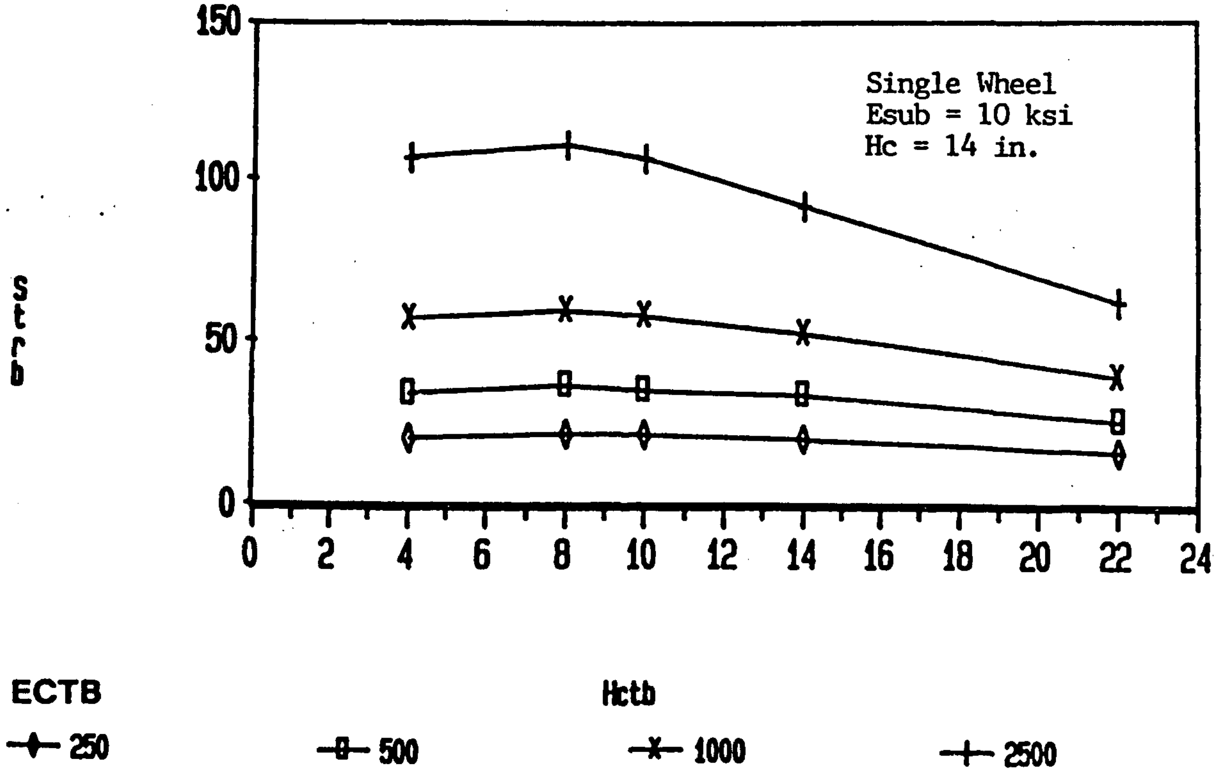

Figure B12. Relationship between Hctb and stress in the CTB for all CTB moduli

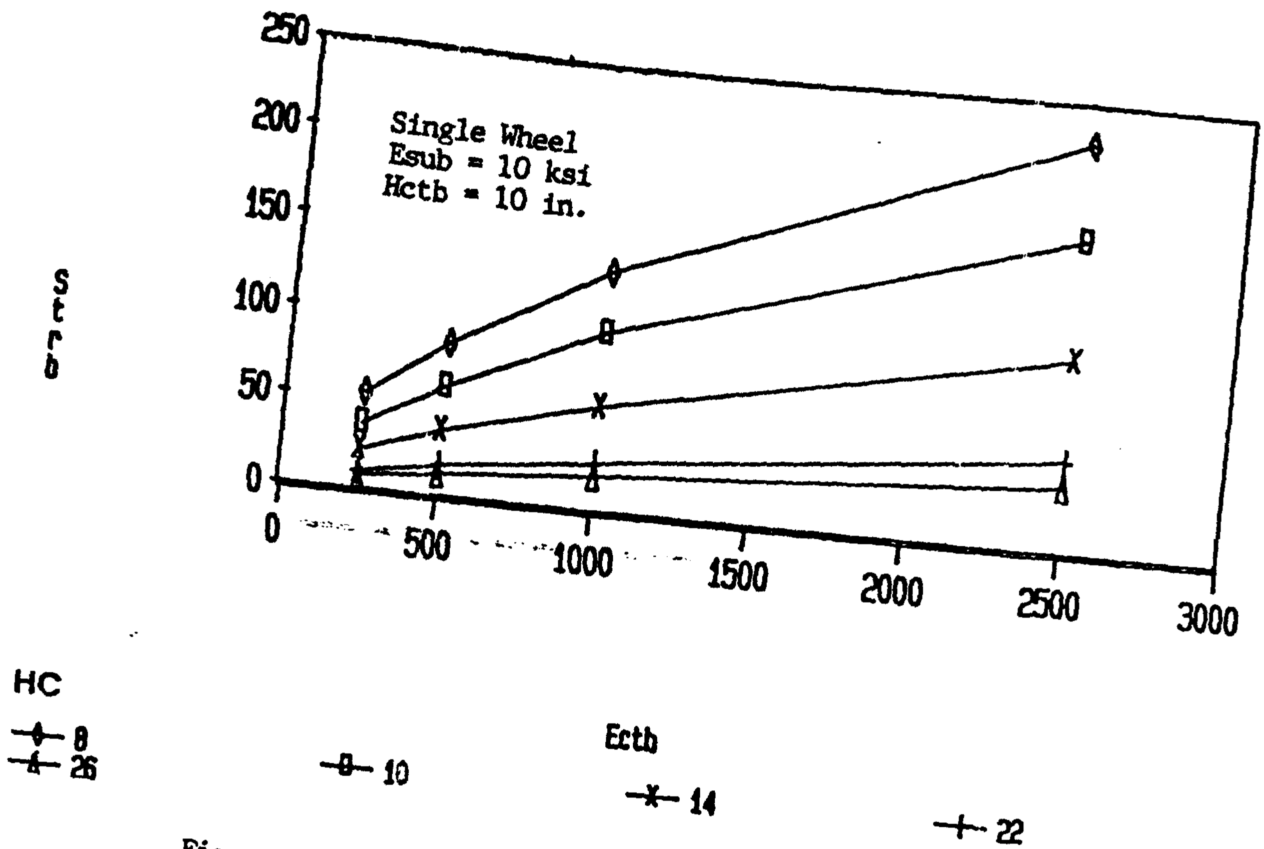

Figure B13. Relationship between Ectb and stress in the CTB for all concrete slab thicknesses

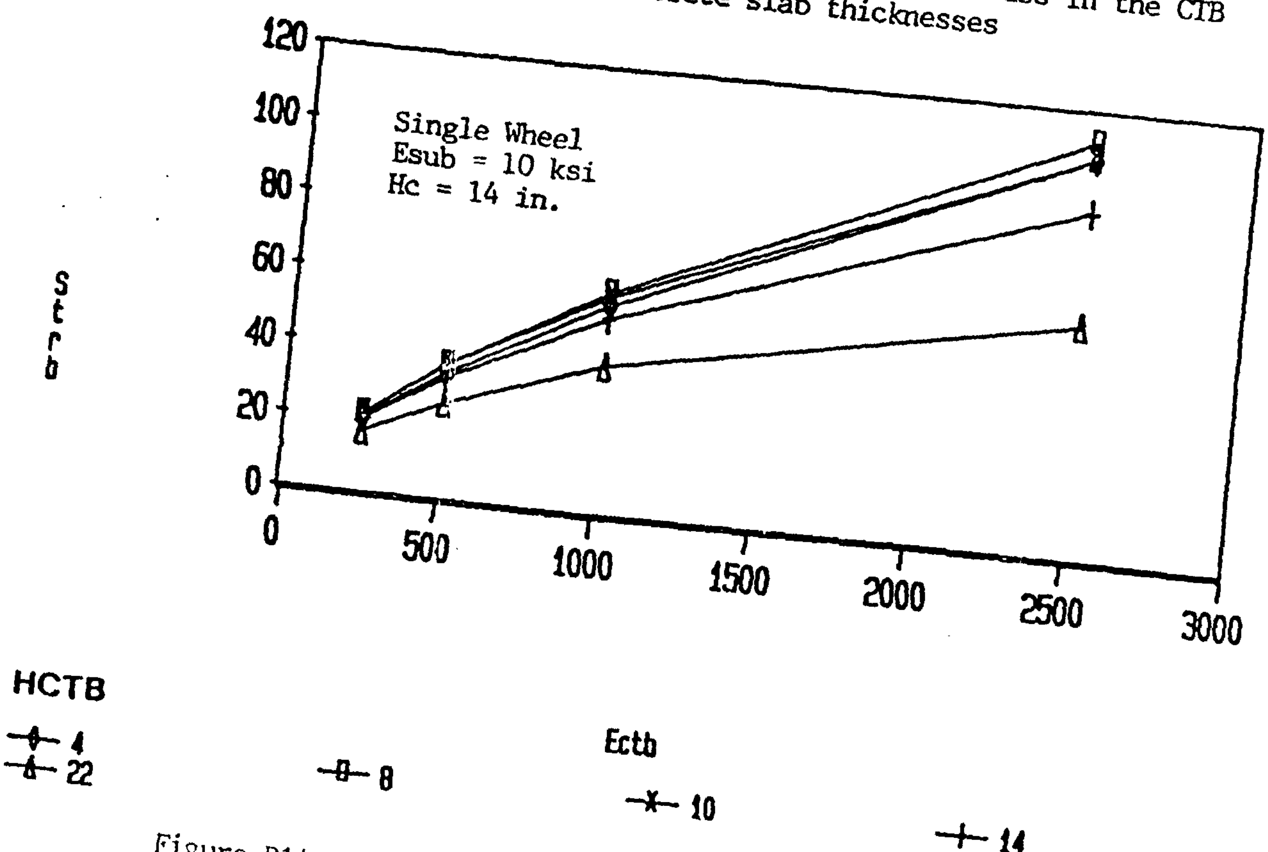

Figure B14. Relationship between Ectb and stress in the CTB for all CTB thicknesses

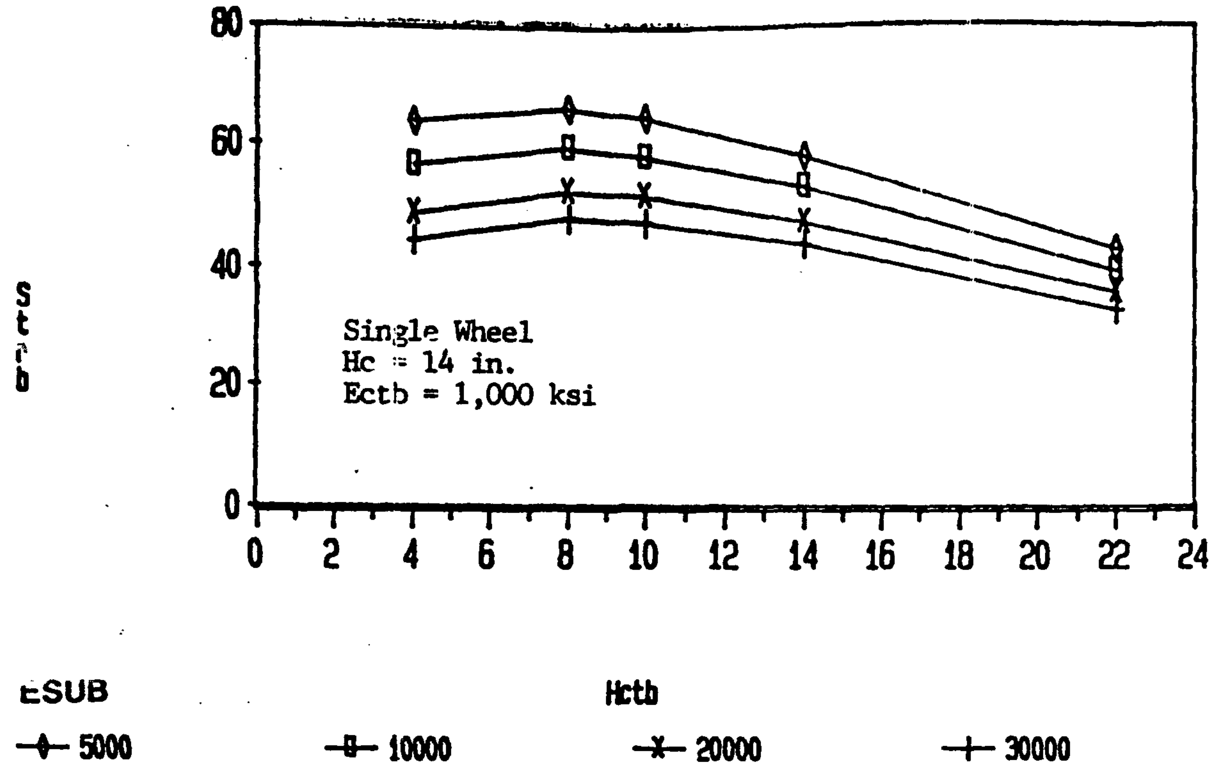

Figure B15. Relationship between Hctb and stress in the CTB for all subgrade moduli

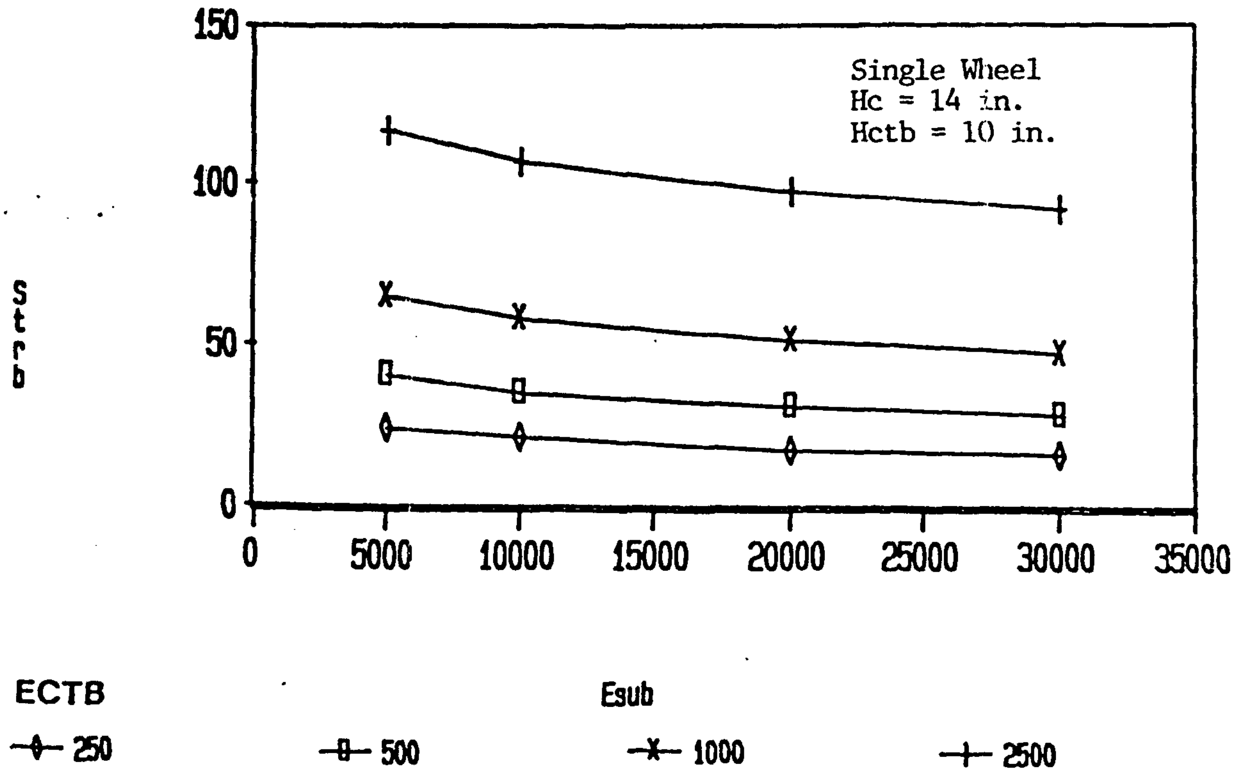

Figure B16. Relationship between subgrade moduli and stress in the CTB for all CTB moduli

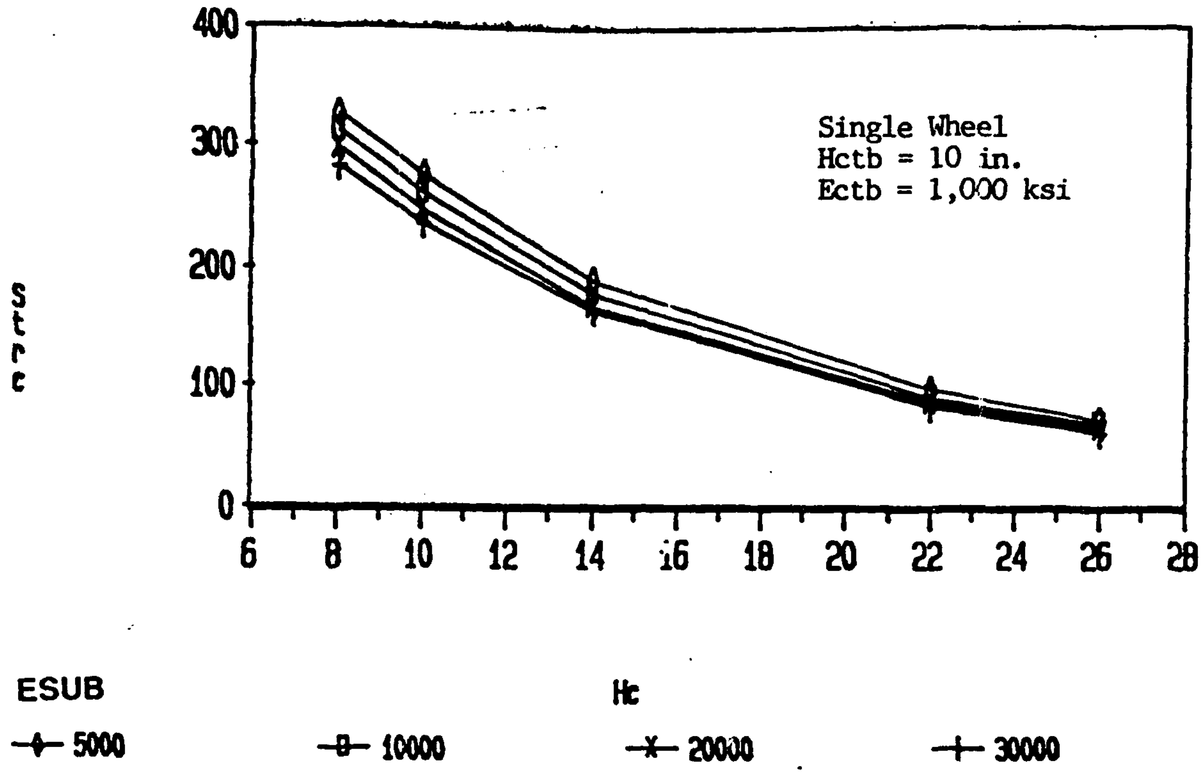

Figure B17. Relationship between concrete slab thickness and stress in the concrete slab for all Esub

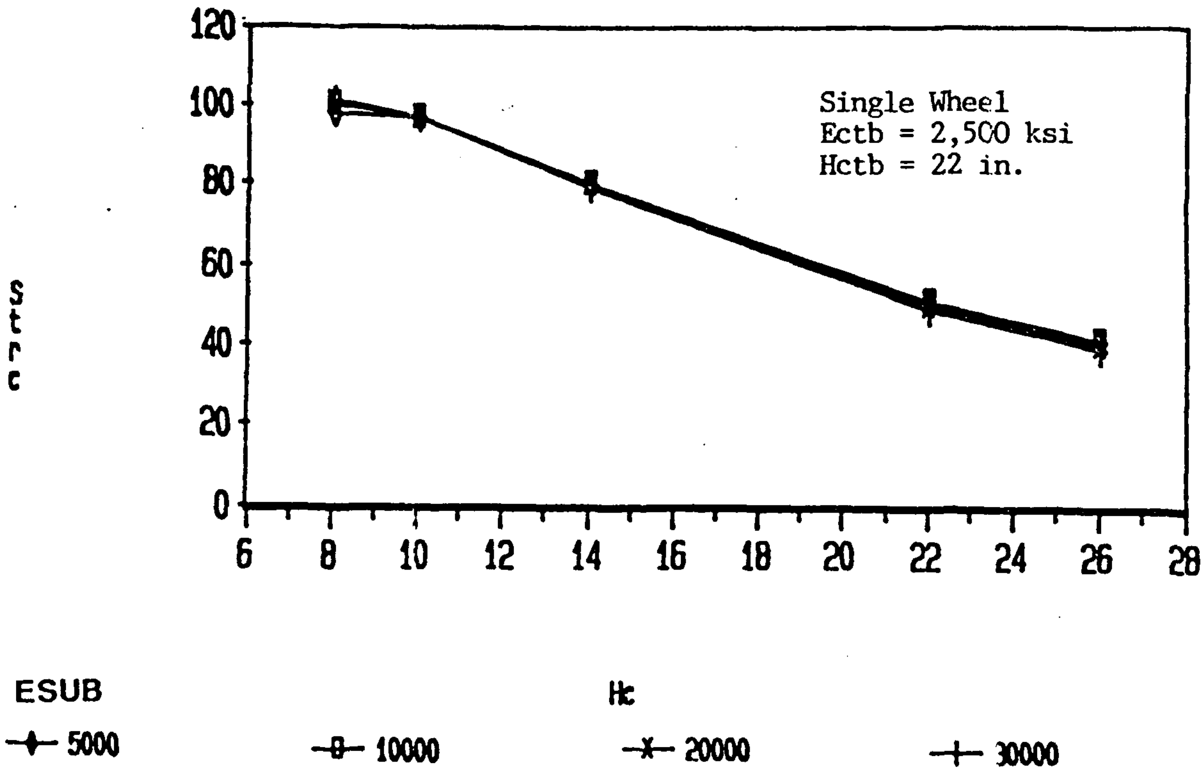

Figure B18. Relationship between concrete slab thickness and stress in the concrete slab for all Esub evaluated at the boundaries of the factorial

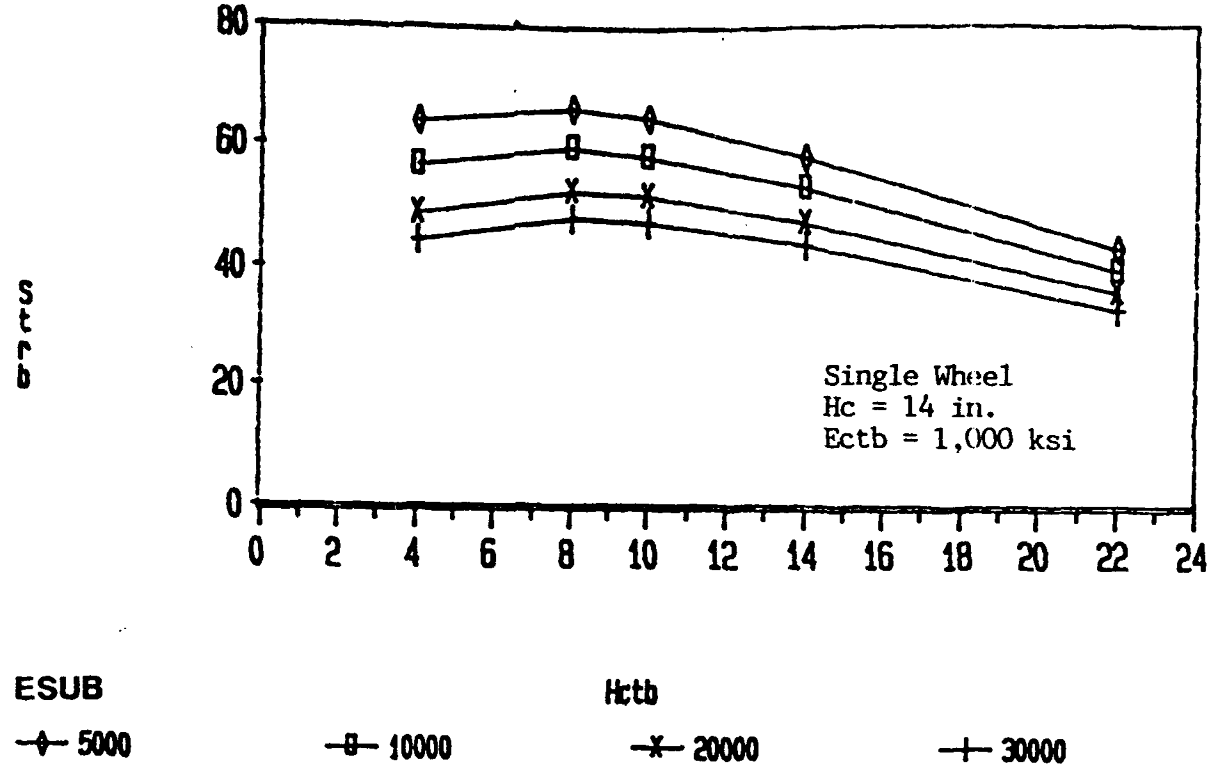

Figure B19. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

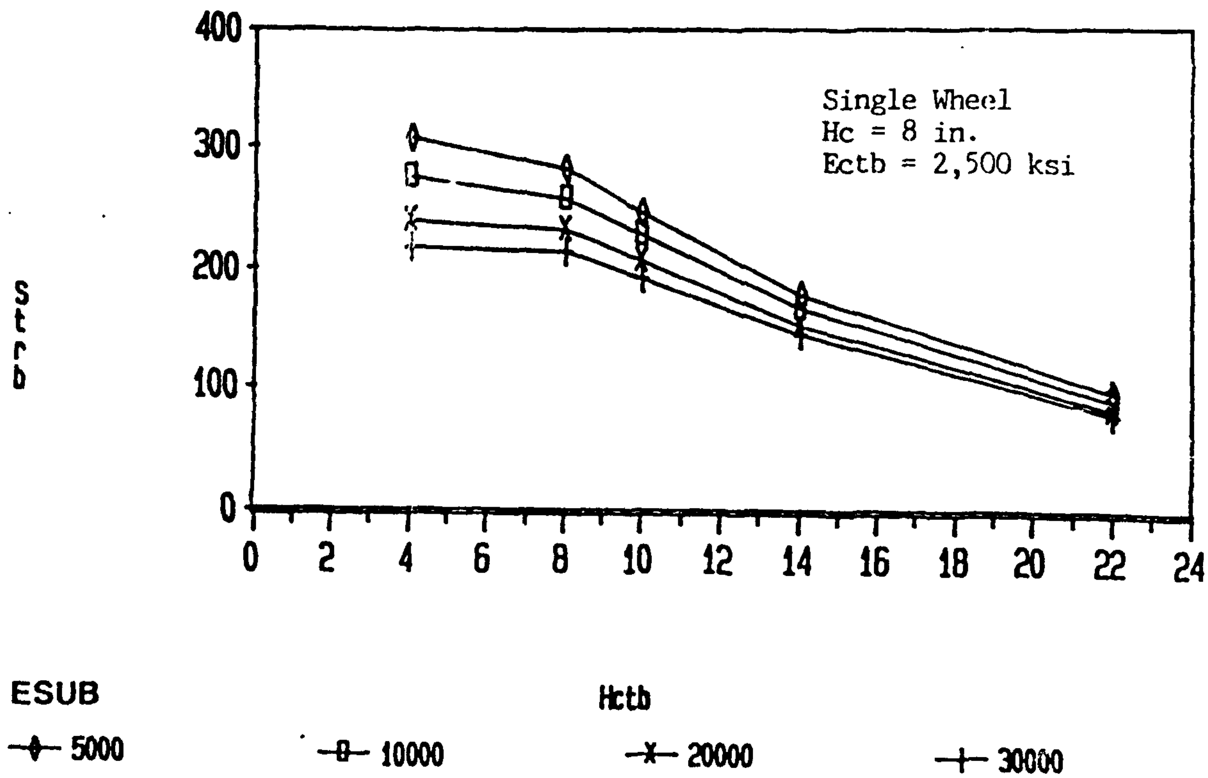

Figure B20. Relationship between CTB thickness and stress in the CTB for all subgrade moduli evaluated at the boundaries of the factorial

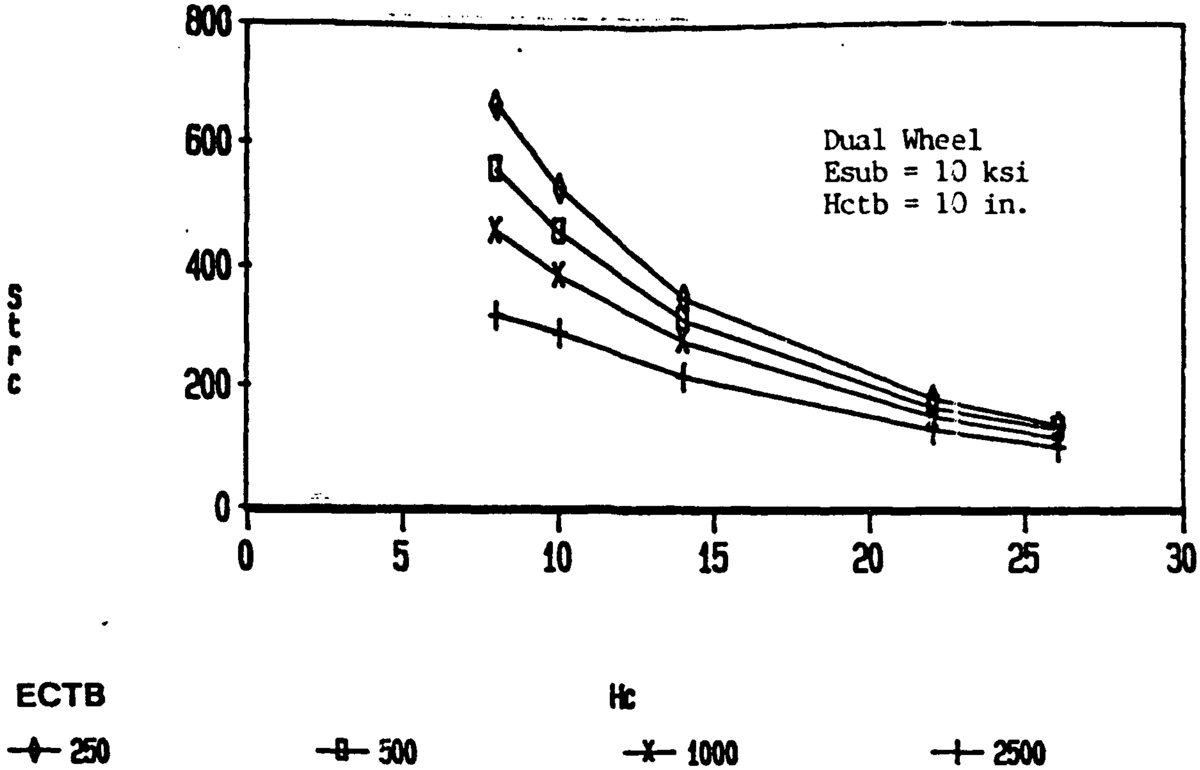

Figure B21. Relationship between concrete slab thickness and stress in the concrete slab for all CTB moduli

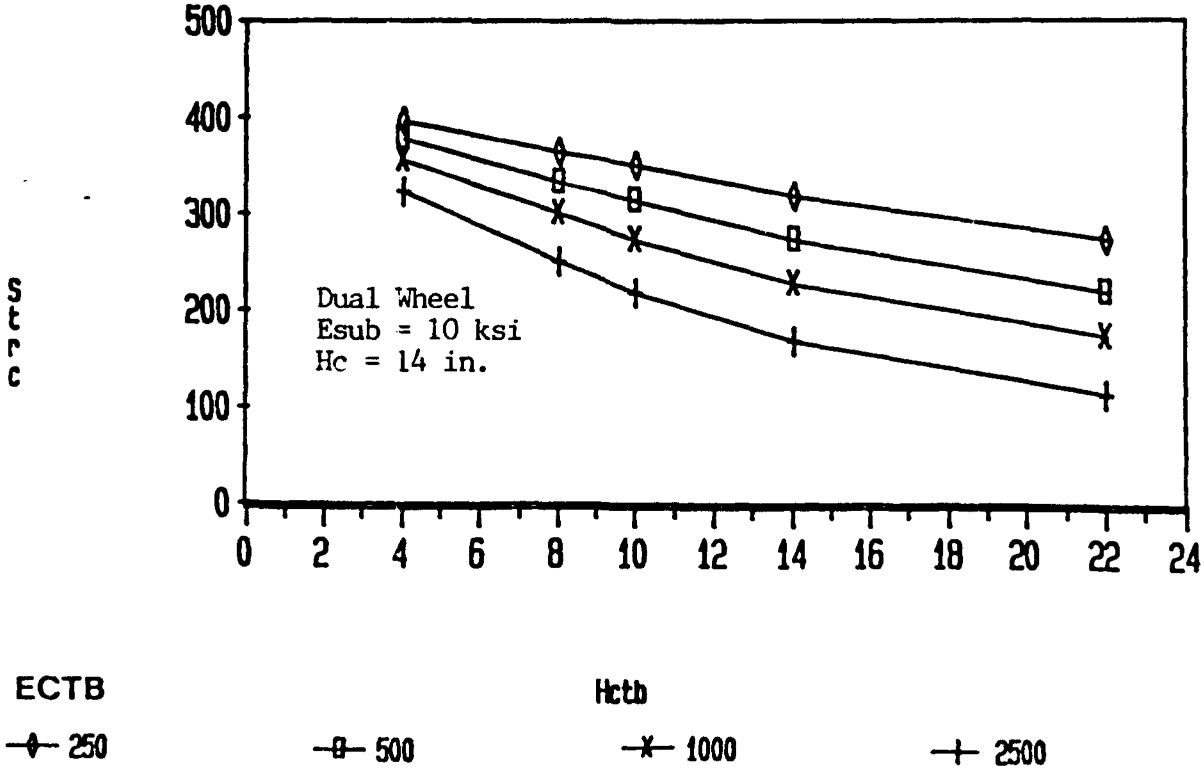

Figure B22. Relationship between CTB thickness and stress in the concrete slab for all CTB moduli

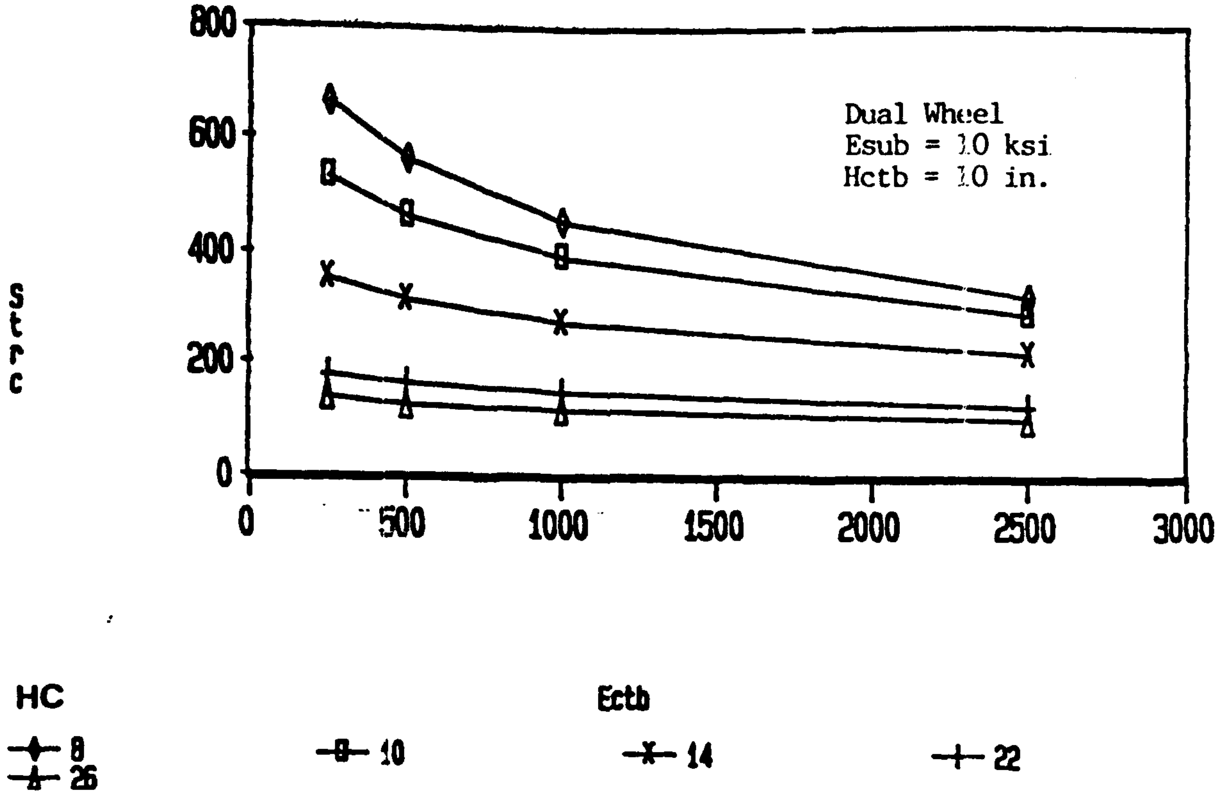

Figure B23. Relationship between Ectb and stress in the concrete slab for all slab thicknesses

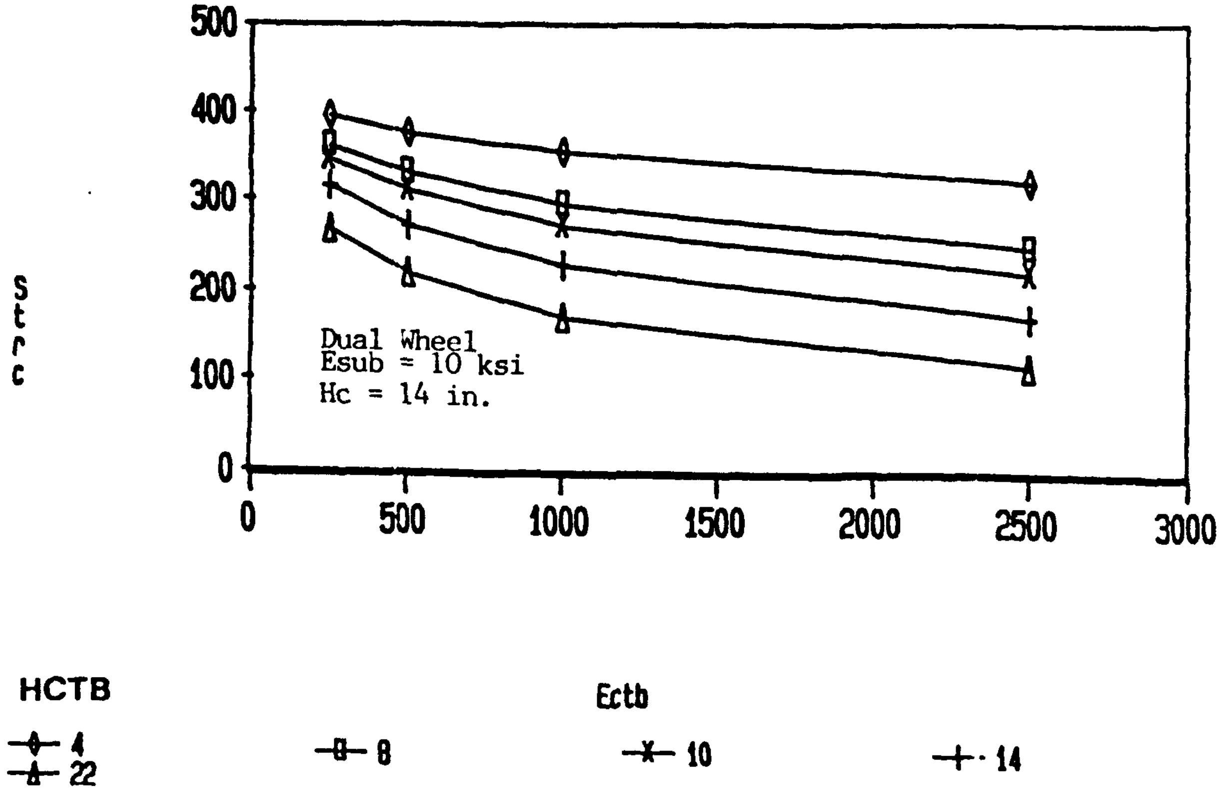

Figure B24. Relationship between Ectb and stress in the concrete slab for all CTB thicknesses

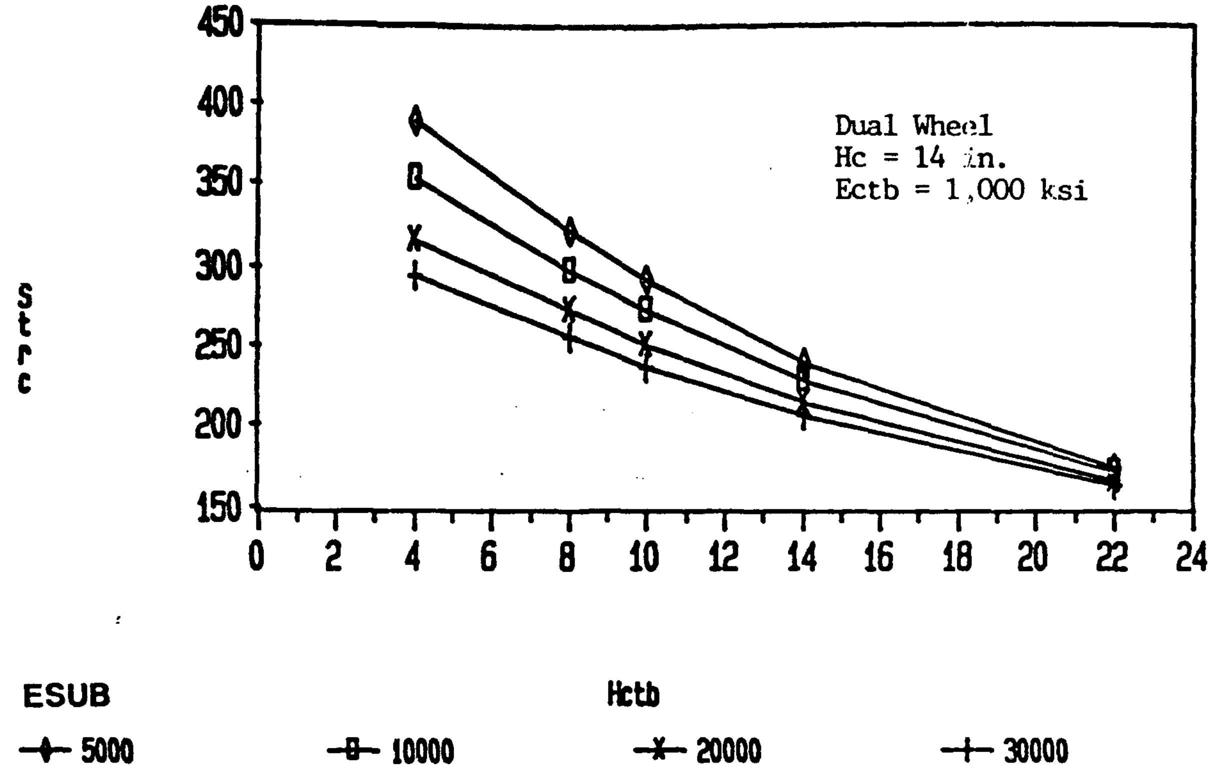

Figure B25. Relationship between CTB thickness and stress in the concrete slab for all subgrade moduli

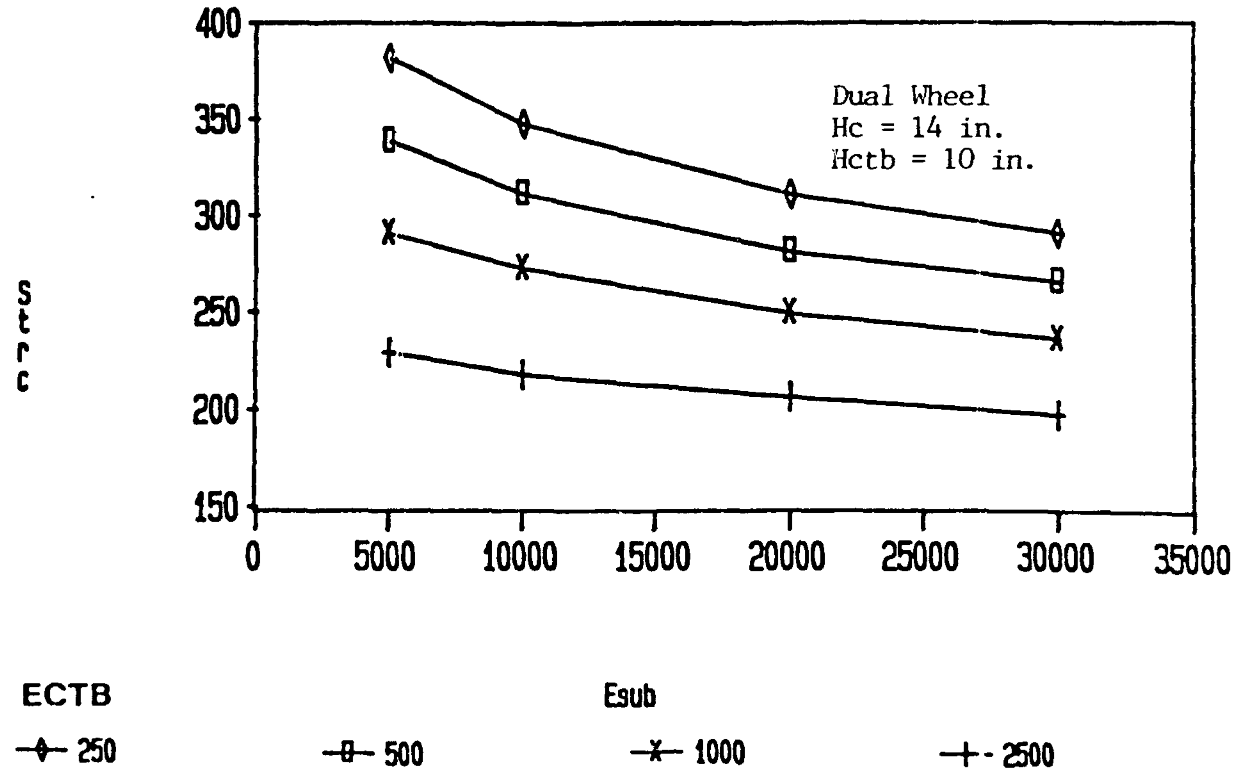

Figure B26. Relationship between subgrade moduli and stress in the concrete slab for all CTB moduli

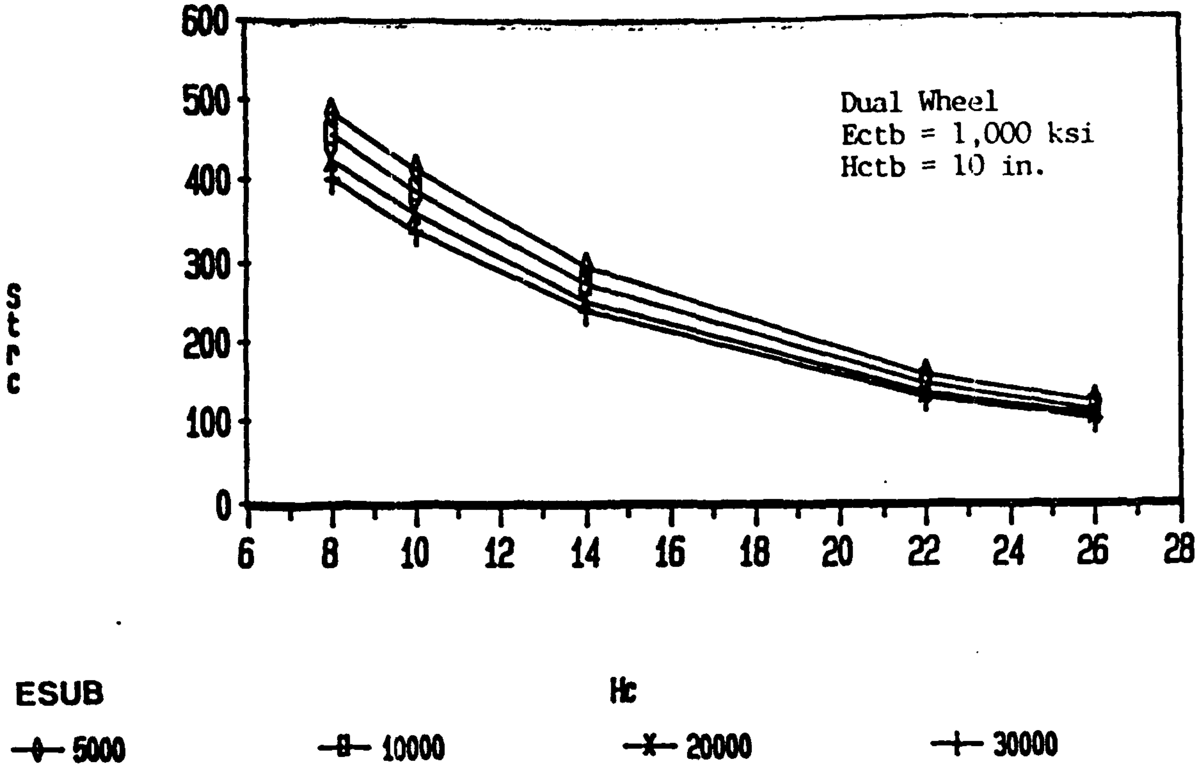

Figure B27. Relationship between concrete slab thickness and stress in the concrete slab for all subgrade moduli

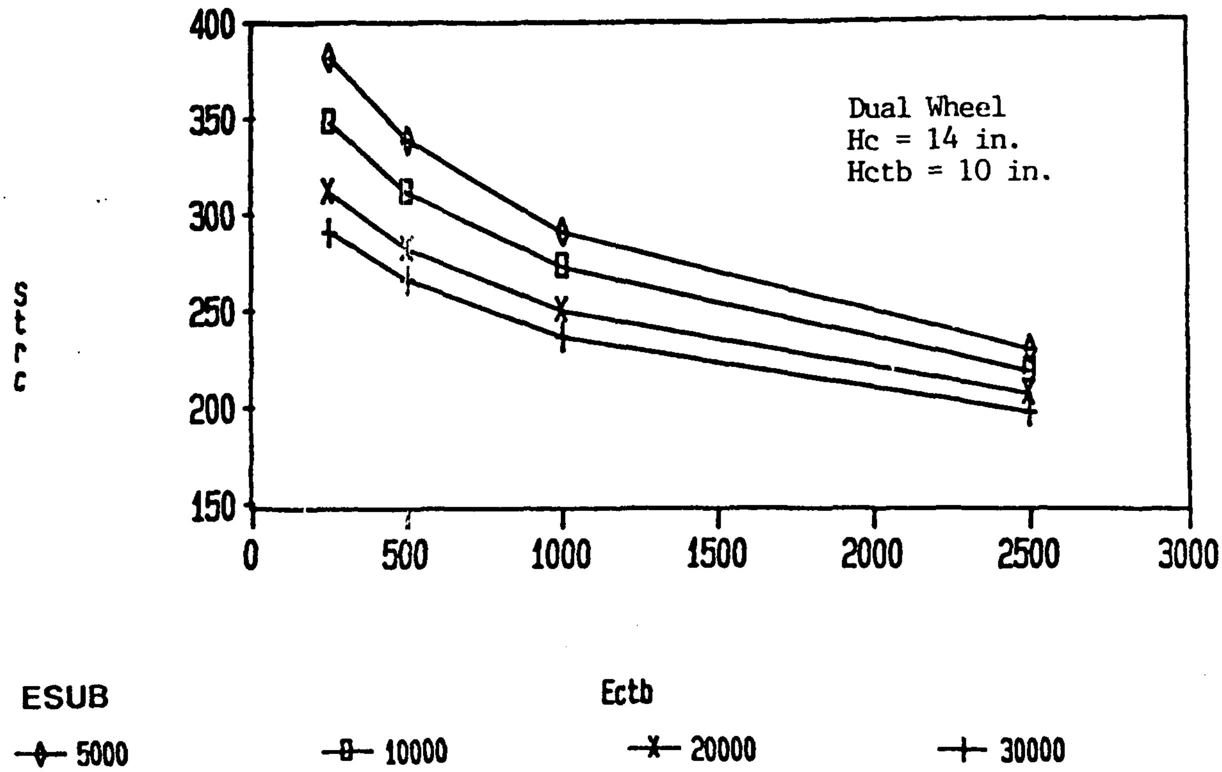

Figure B28. Relationship between CTB moduli and stress in the concrete slab for all subgrade moduli

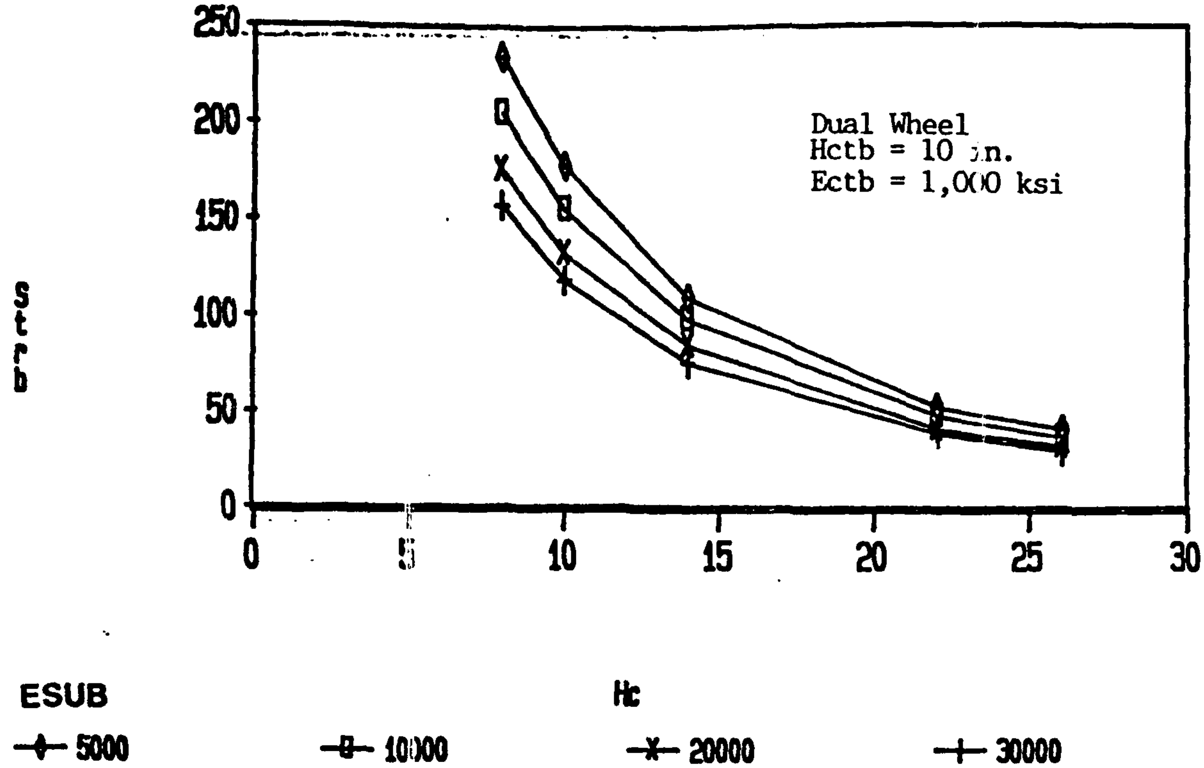

Figure B29. Relationship between concrete slab thickness and stress in the CTB for all subgrade moduli

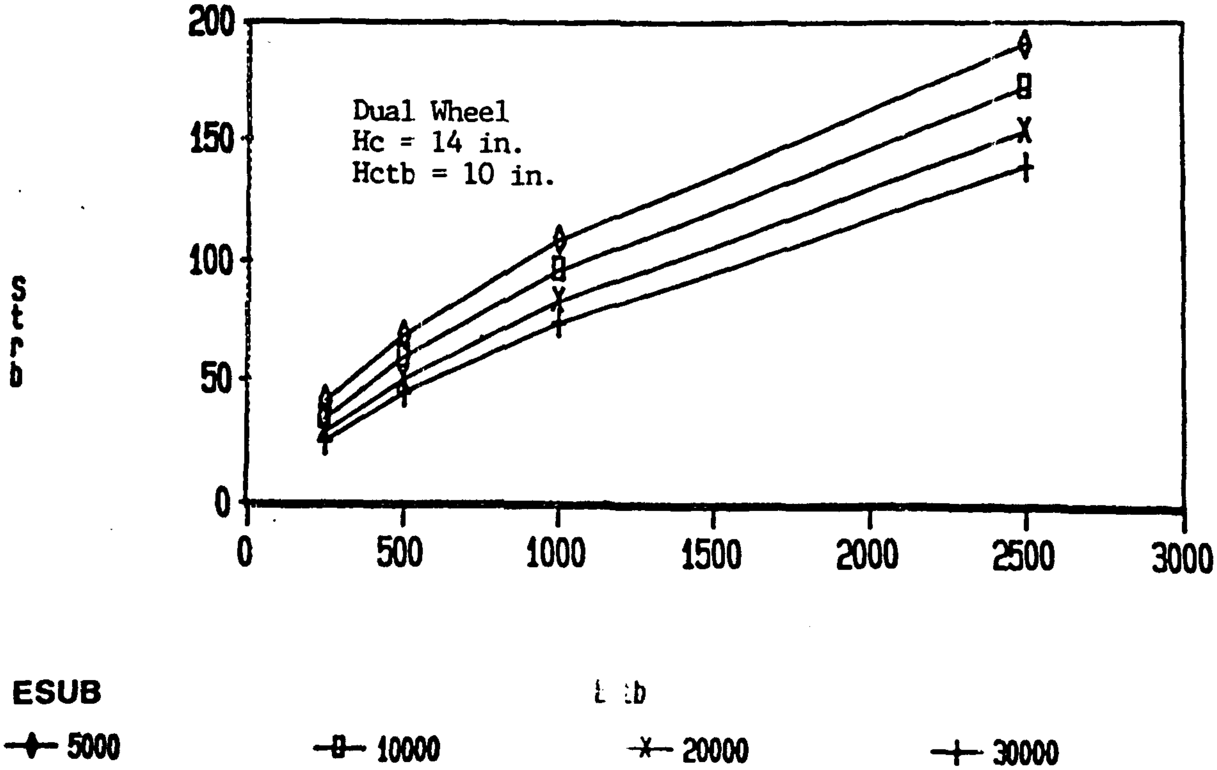

Figure B30. Relationship between CTB moduli and stress in the CTB for all subgrade moduli

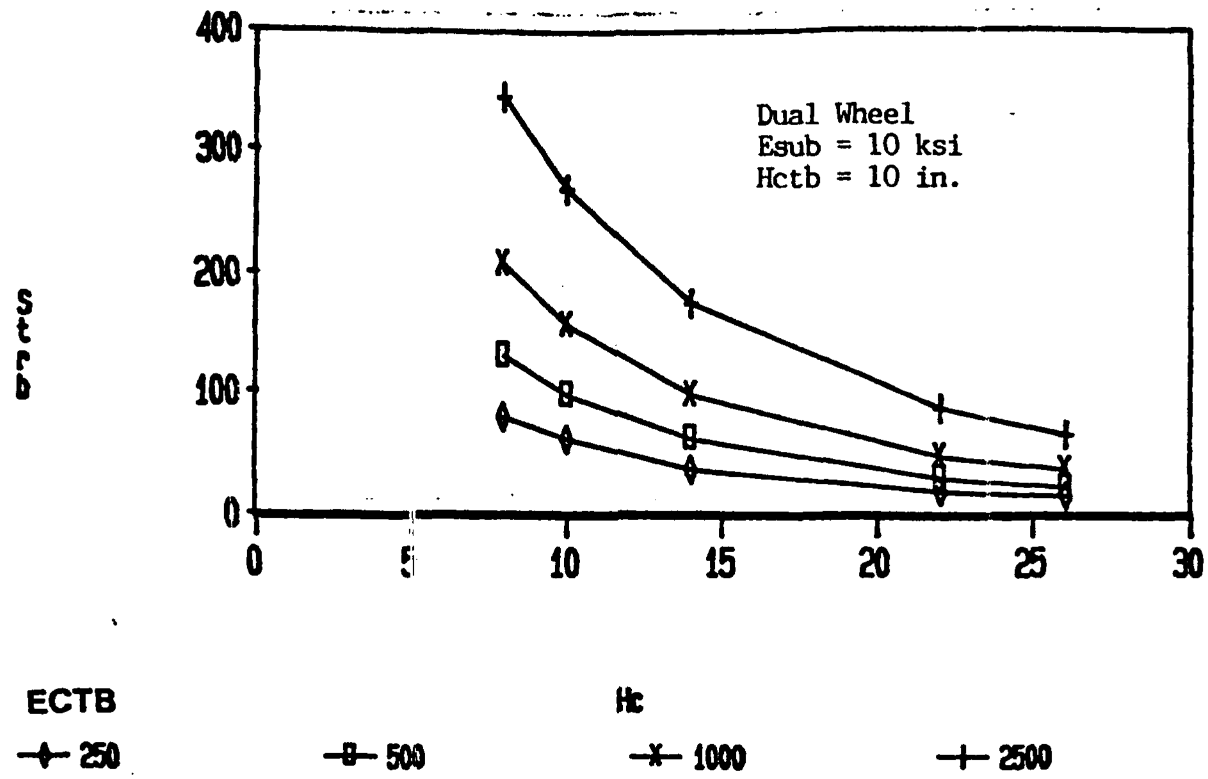

Figure B31. Relationship between concrete slab thickness and stress in the CTB for all CTB moduli

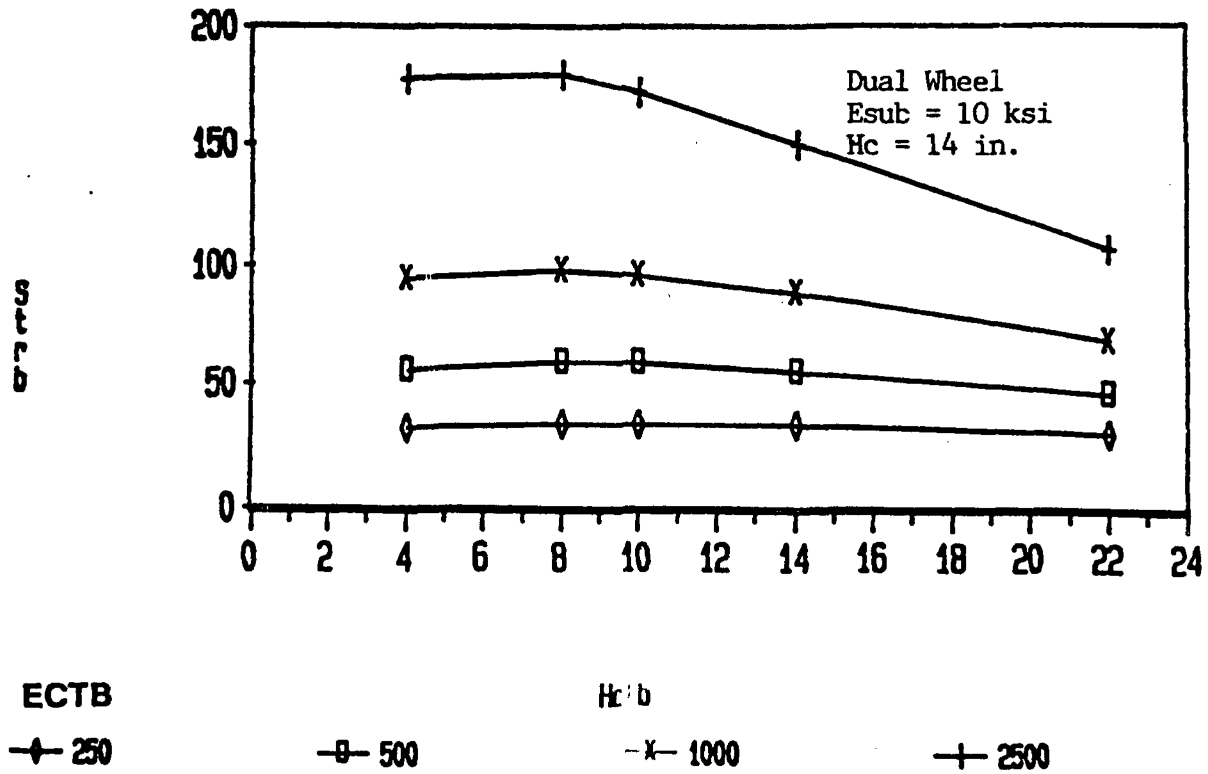

Figure B32. Relationship between CTB thickness and stress in the CTB for all CTB moduli

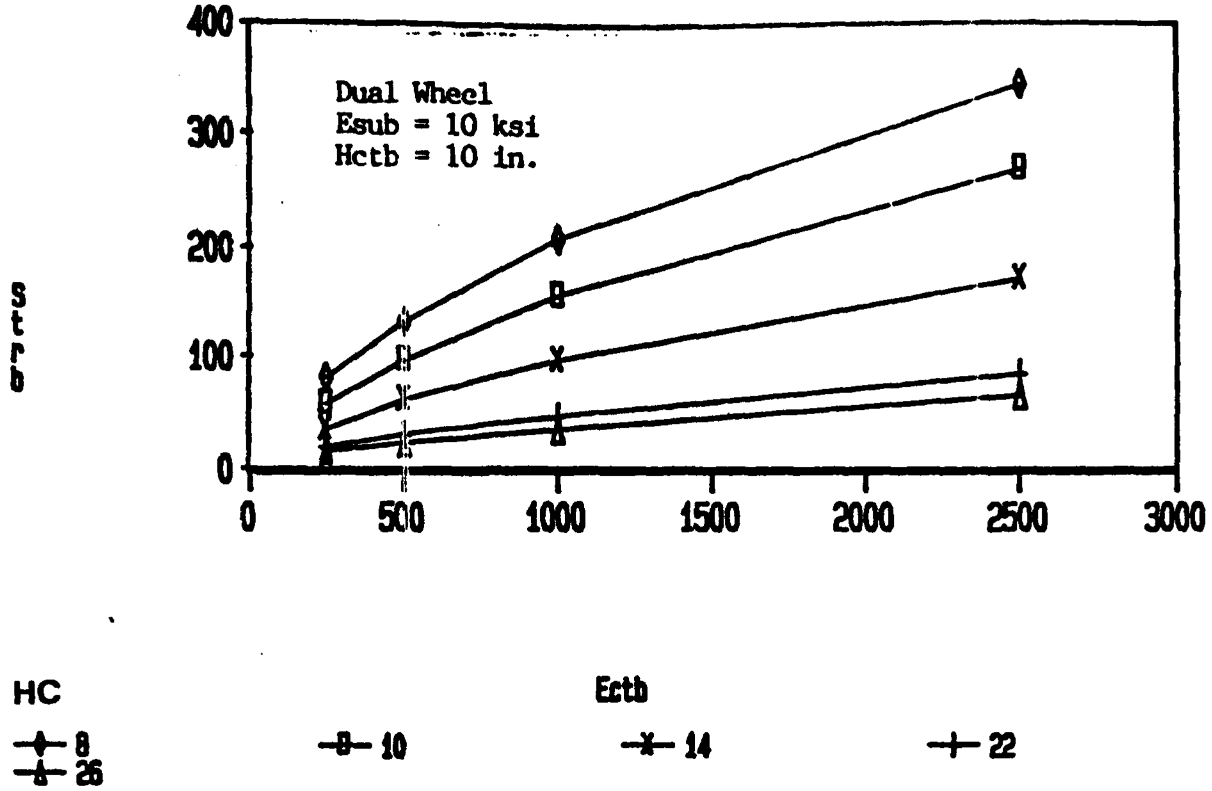

Figure B33. Relationship between CTB moduli and stress in the CTB for all concrete thicknesses

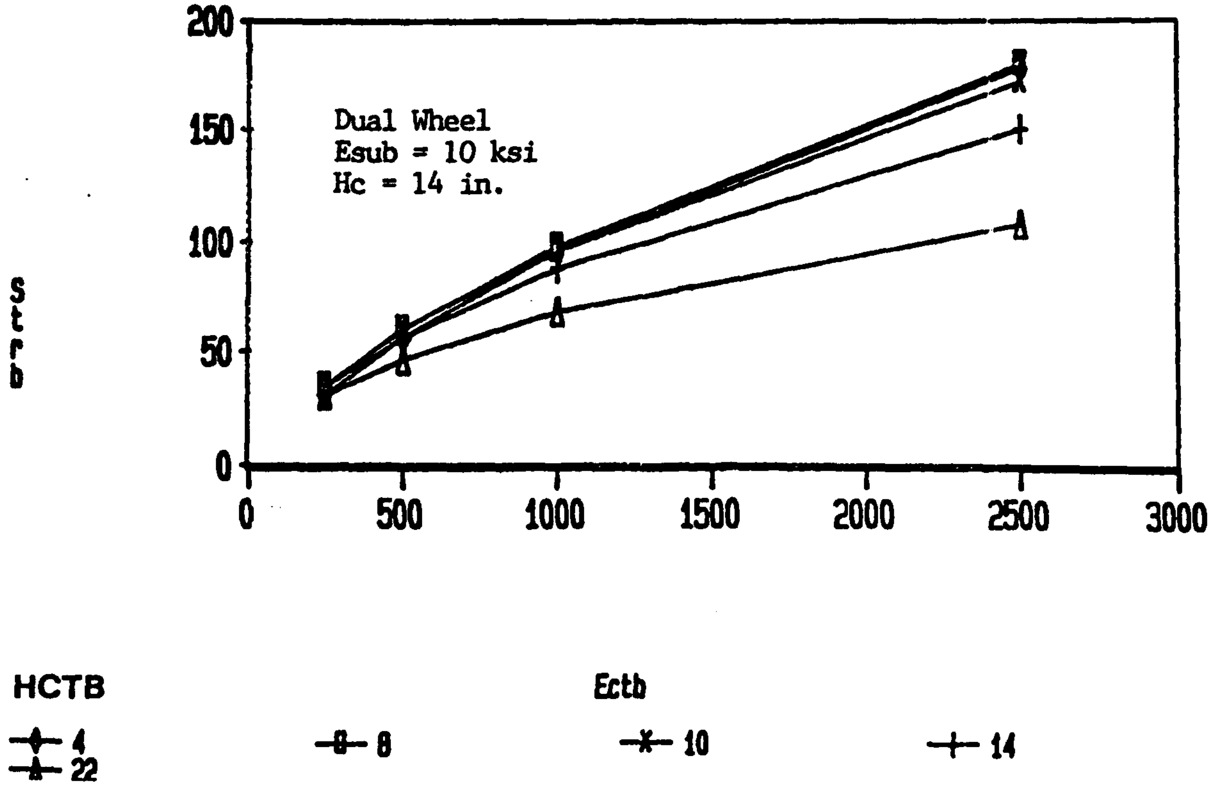

Figure B34. Relationship between CTB moduli and stress in the CTB for all CTB thicknesses

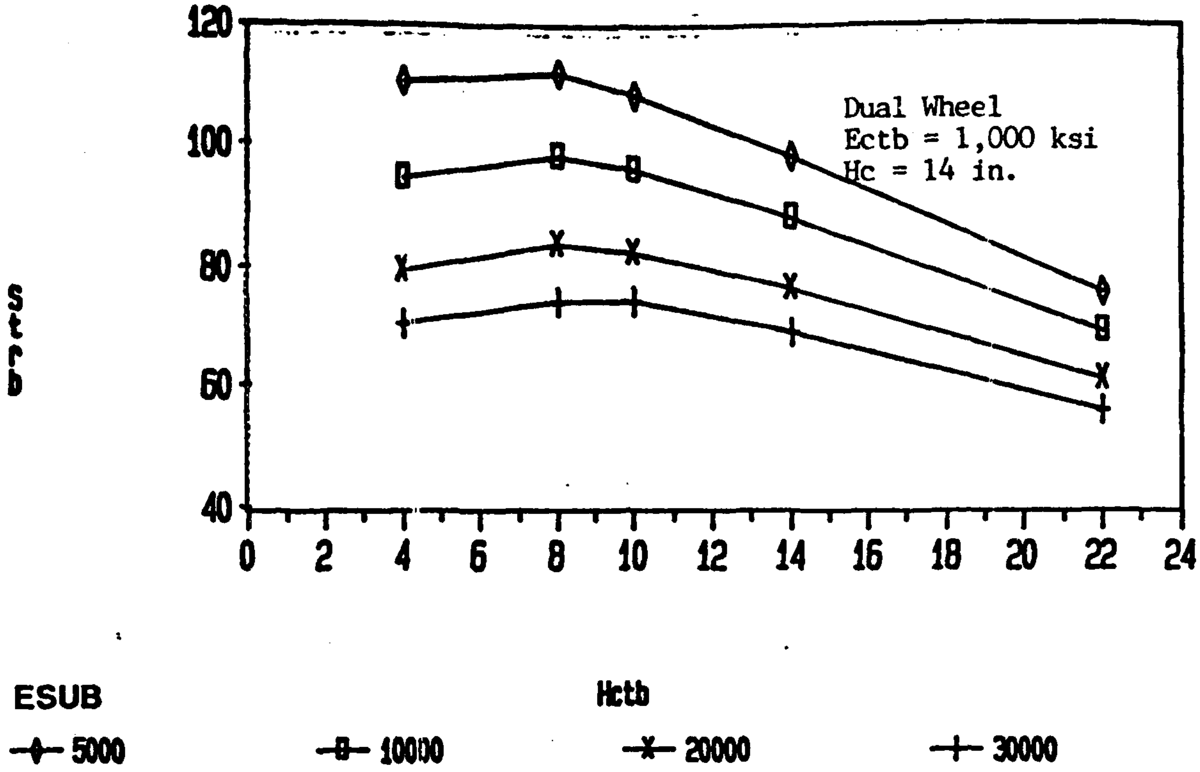

Figure B35. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

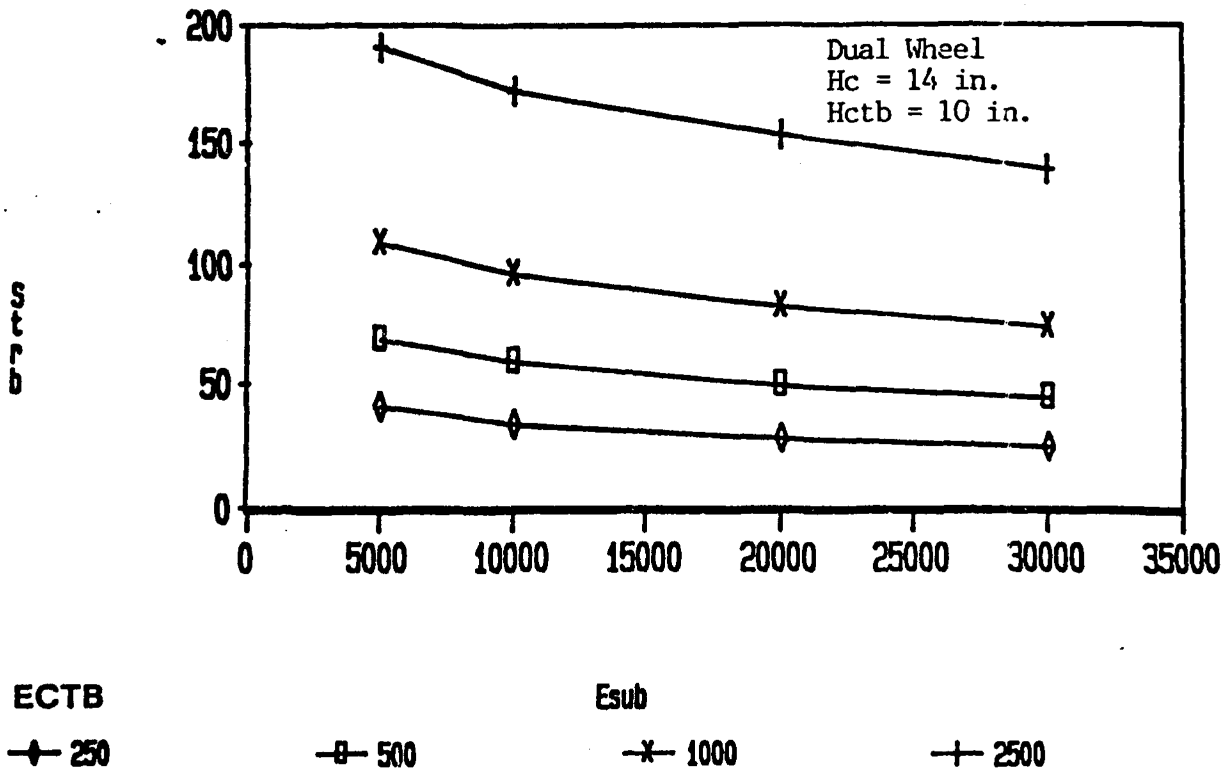

Figure B36. Relationship between subgrade moduli and stress in the CTB for all CTB moduli

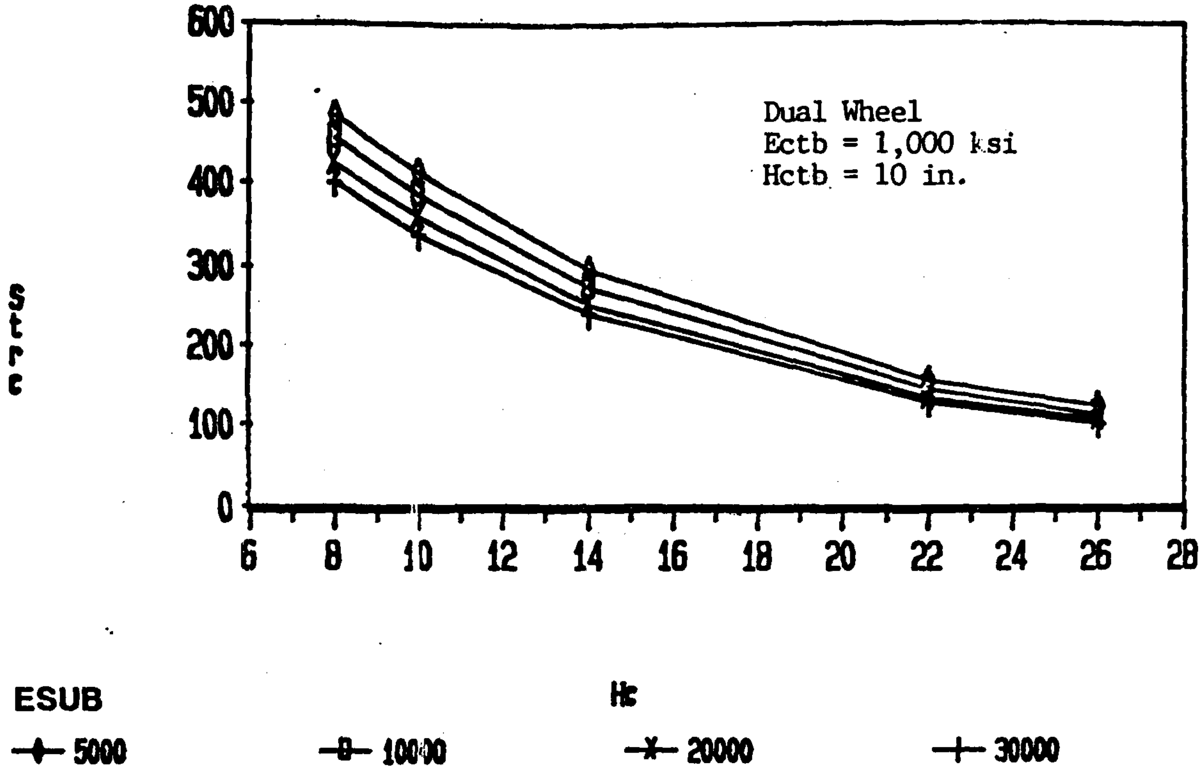

Figure B37. Relationship between concrete slab thickness and stress in the concrete slab for all Esub

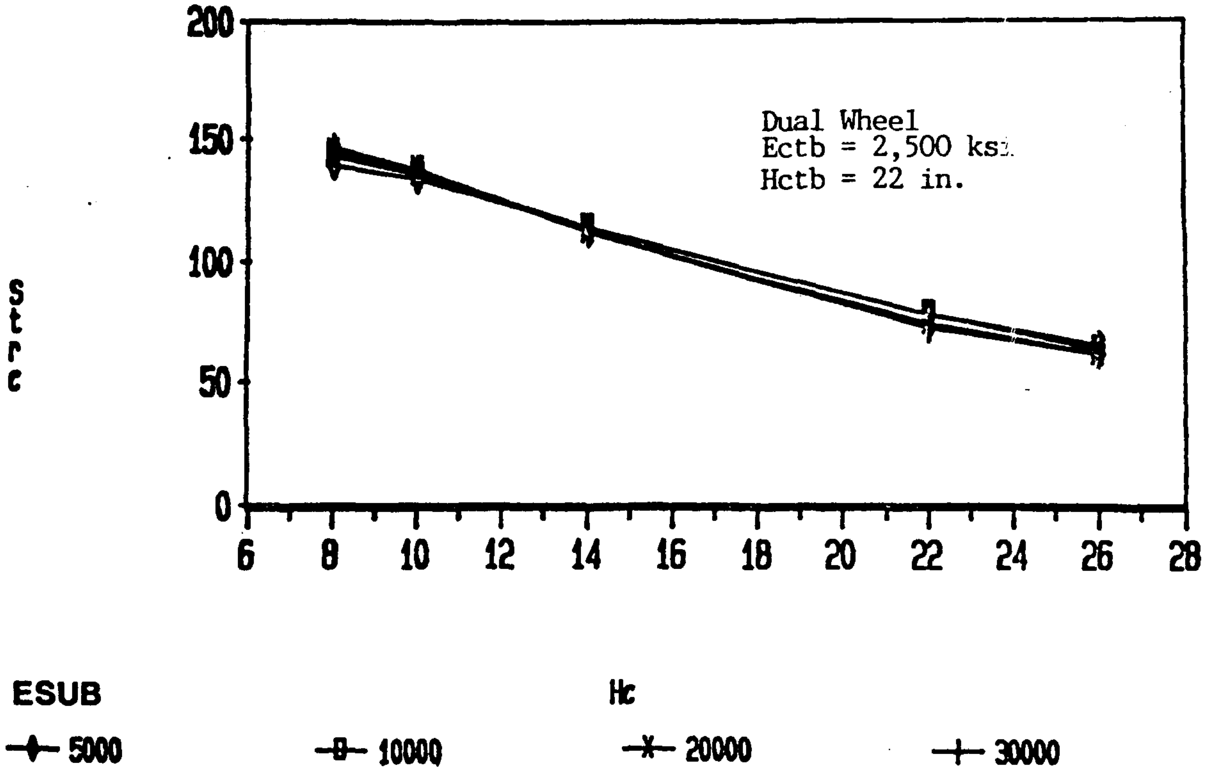

Figure B38. Relationship between concrete slab thickness and stress in the concrete slab for all Esub evaluated at the boundaries of the factorial

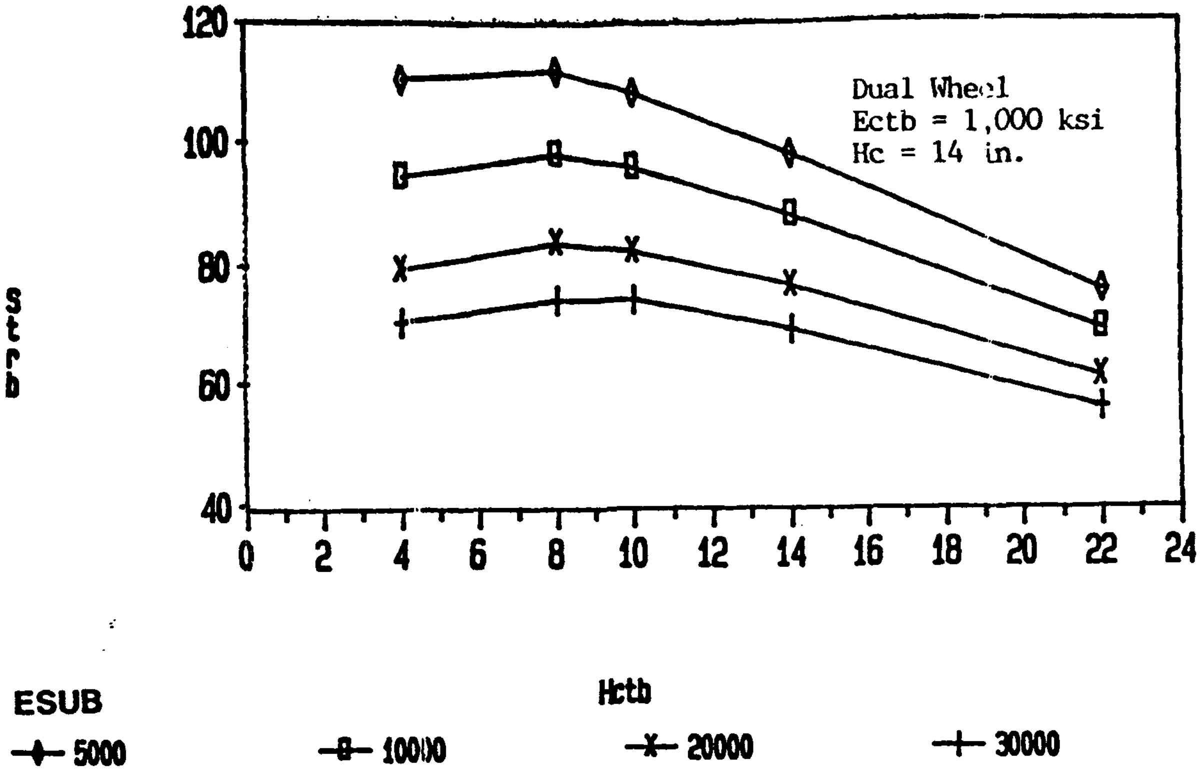

Figure B39. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

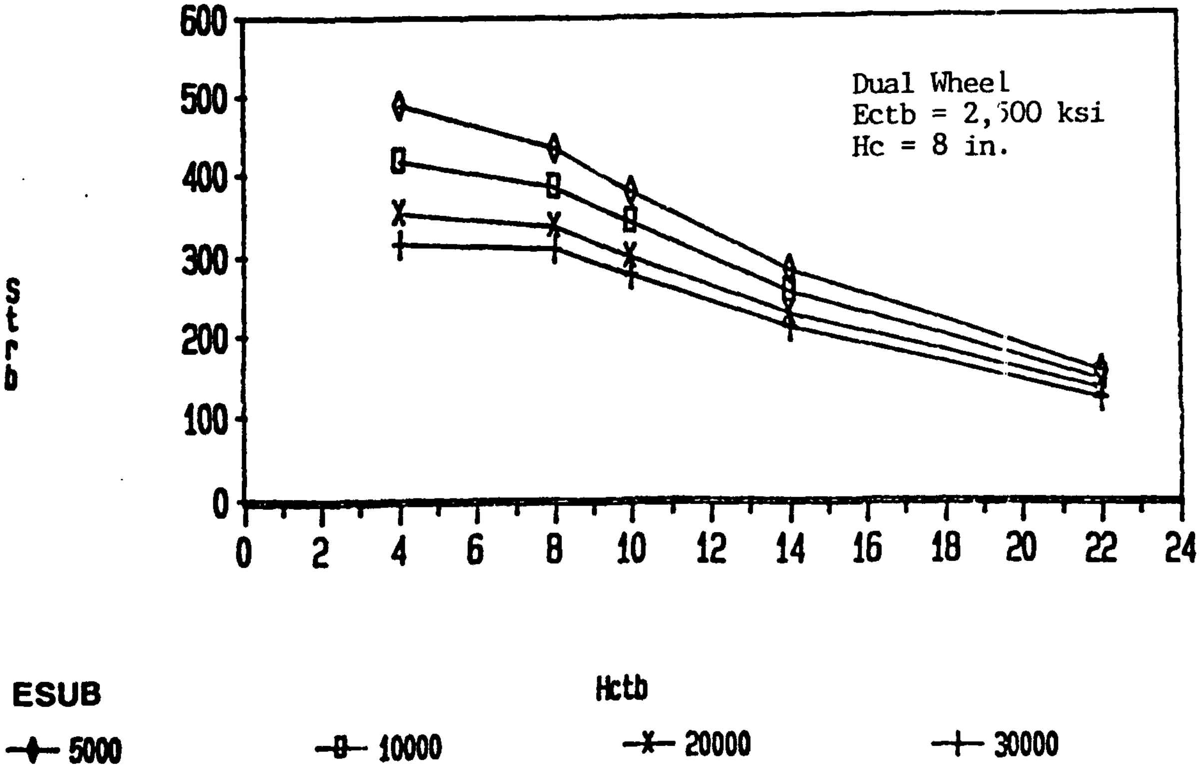

Figure B40. Relationship between CTB thickness and stress in the CTB for all subgrade moduli evaluated at the boundaries of the factorial

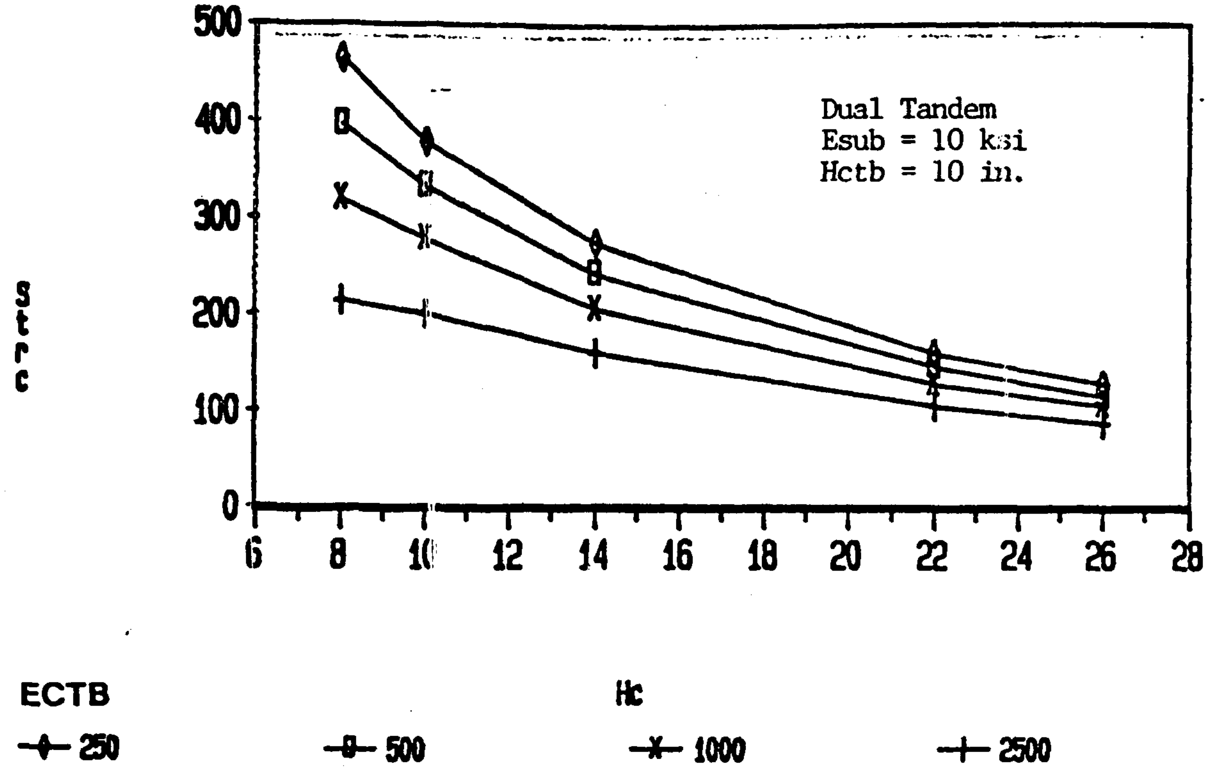

Figure B41. Relationship between concrete slab thickness and stress in the concrete for all CTB moduli

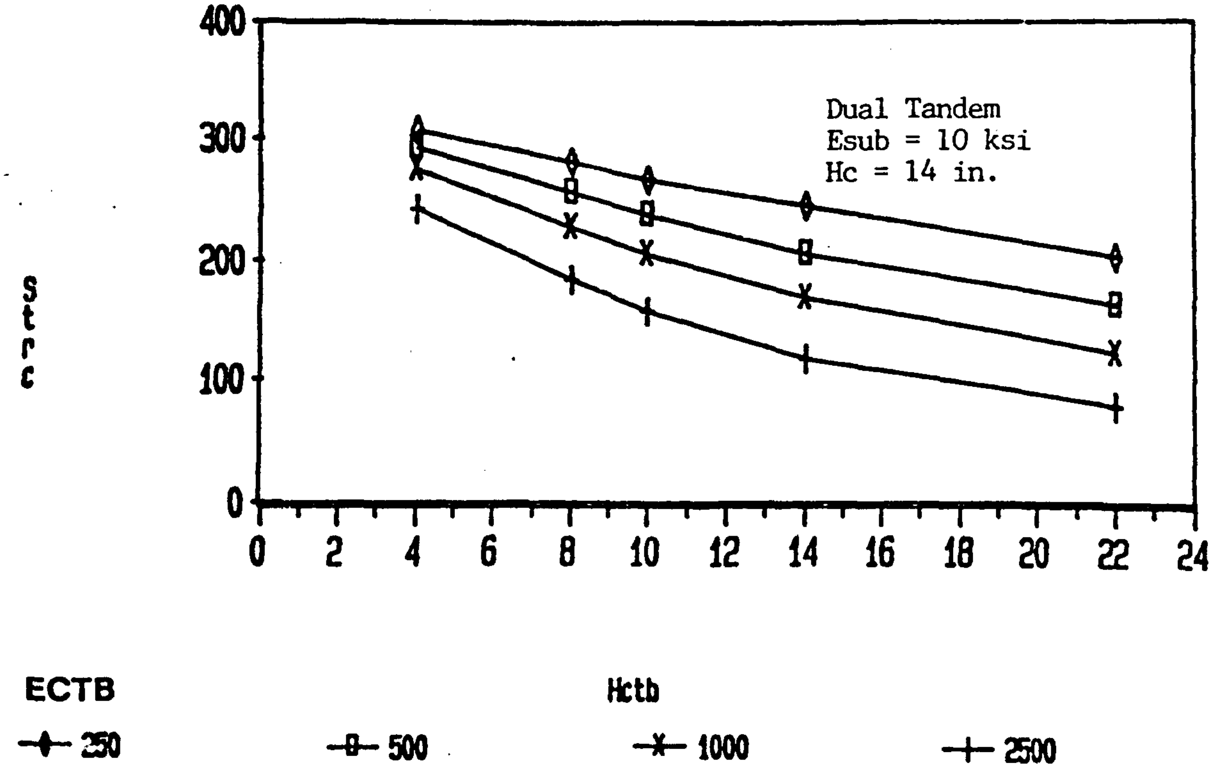

Figure B42. Relationship between CTB thickness and stress in the concrete for all CTB moduli

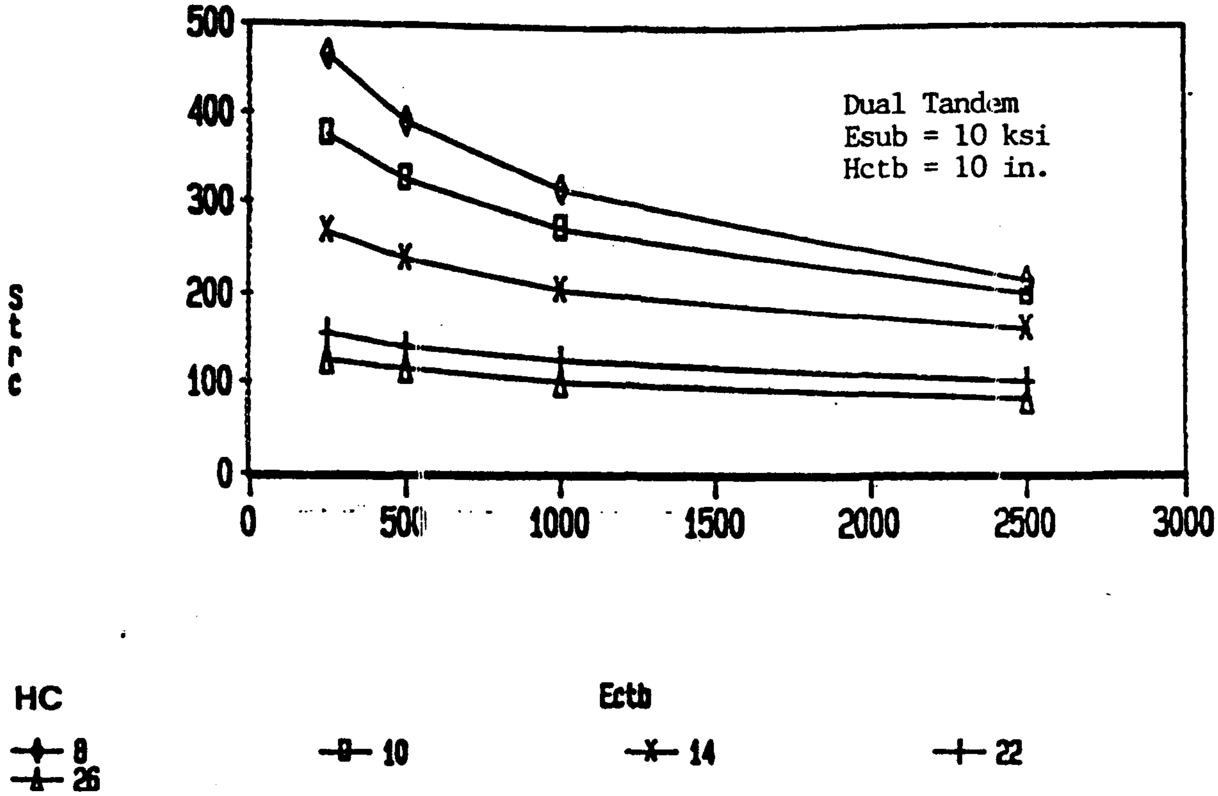

Figure B43. Relationship between CTB moduli and stress in the concrete for all concrete thicknesses

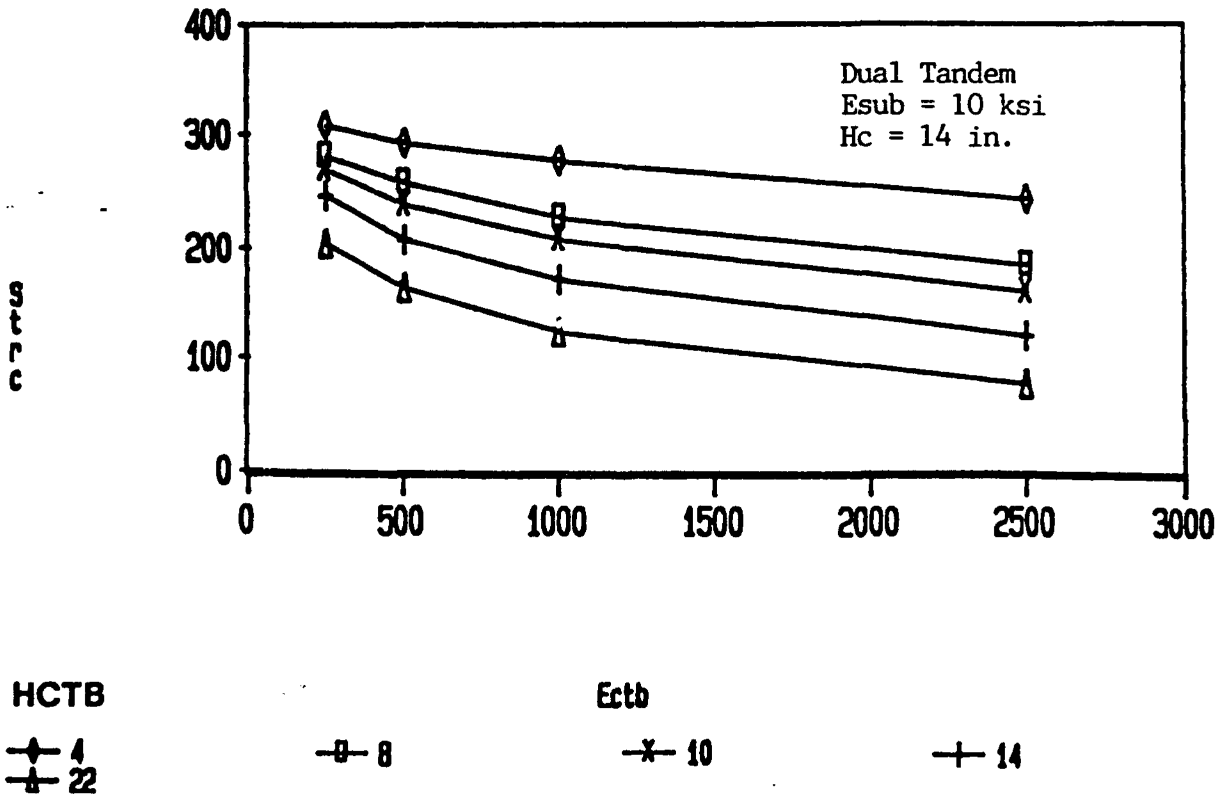

Figure B44. Relationship between CTB moduli and stress in the concrete for all CTB thicknesses

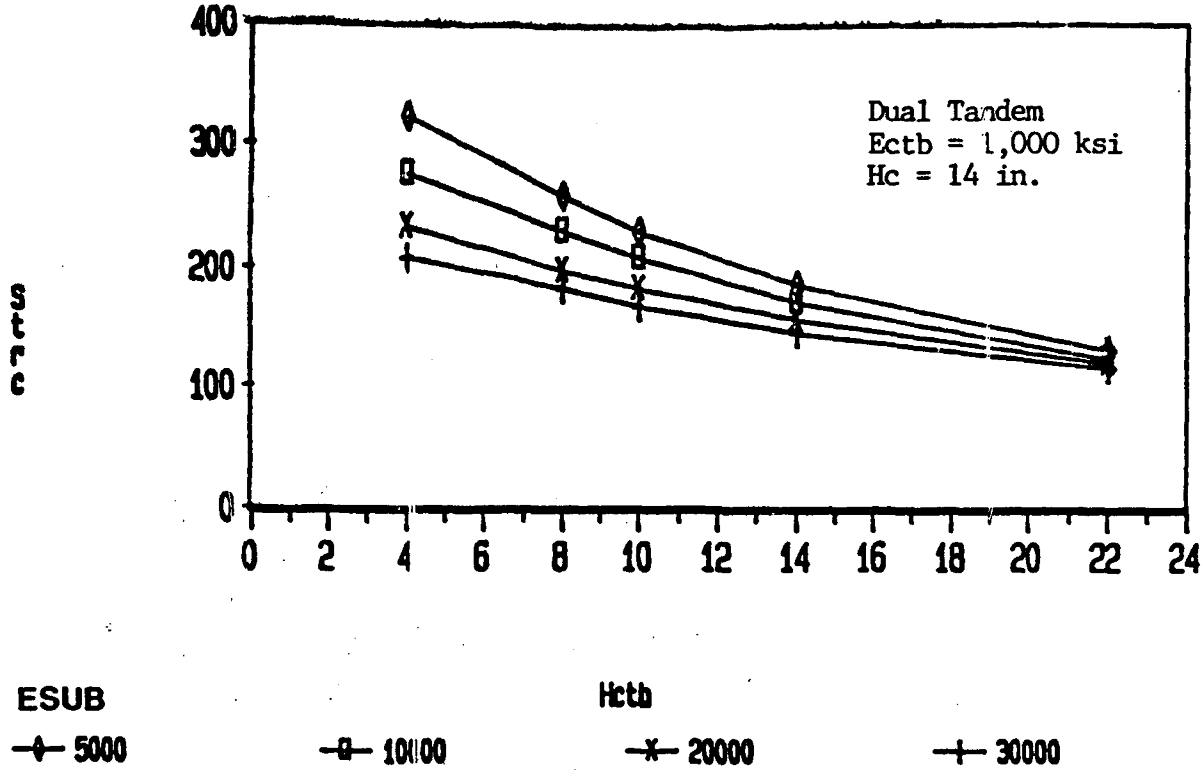

Figure B45. Relationship between CTB thickness and stress in the concrete for all subgrade moduli

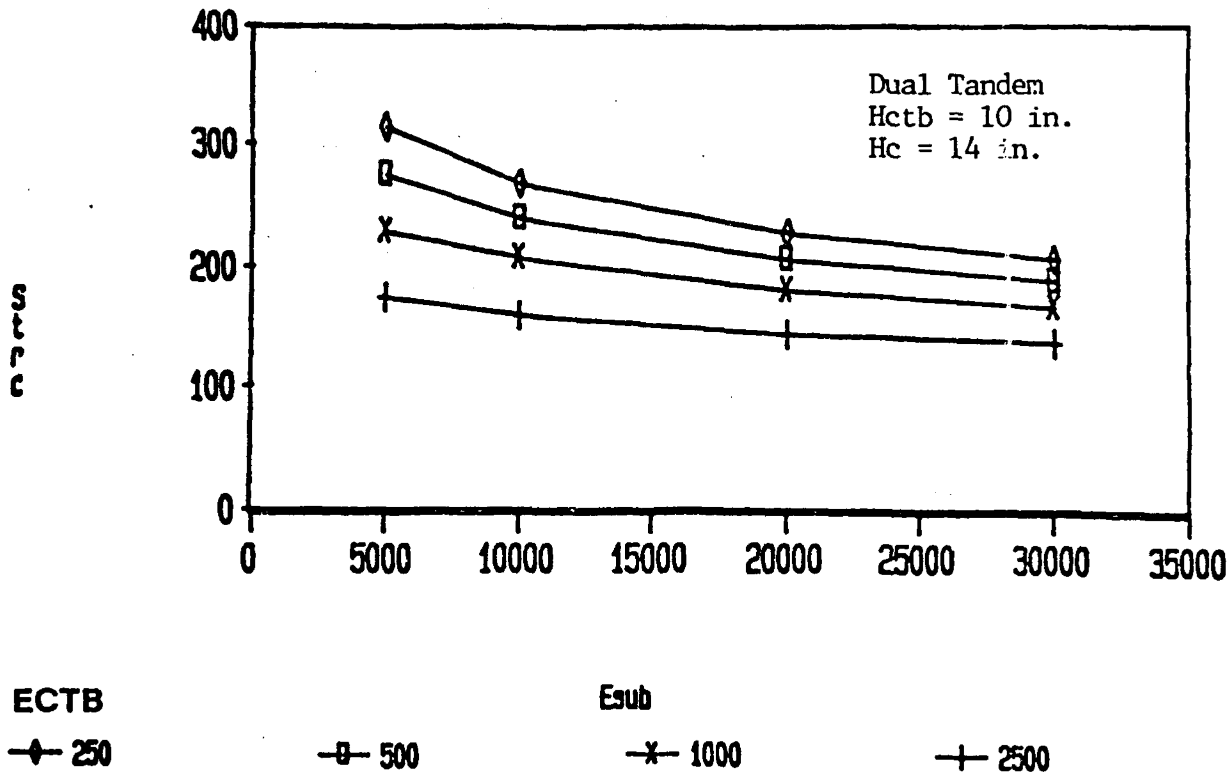

Figure B46. Relationship between subgrade moduli and stress in the concrete for all CTB moduli

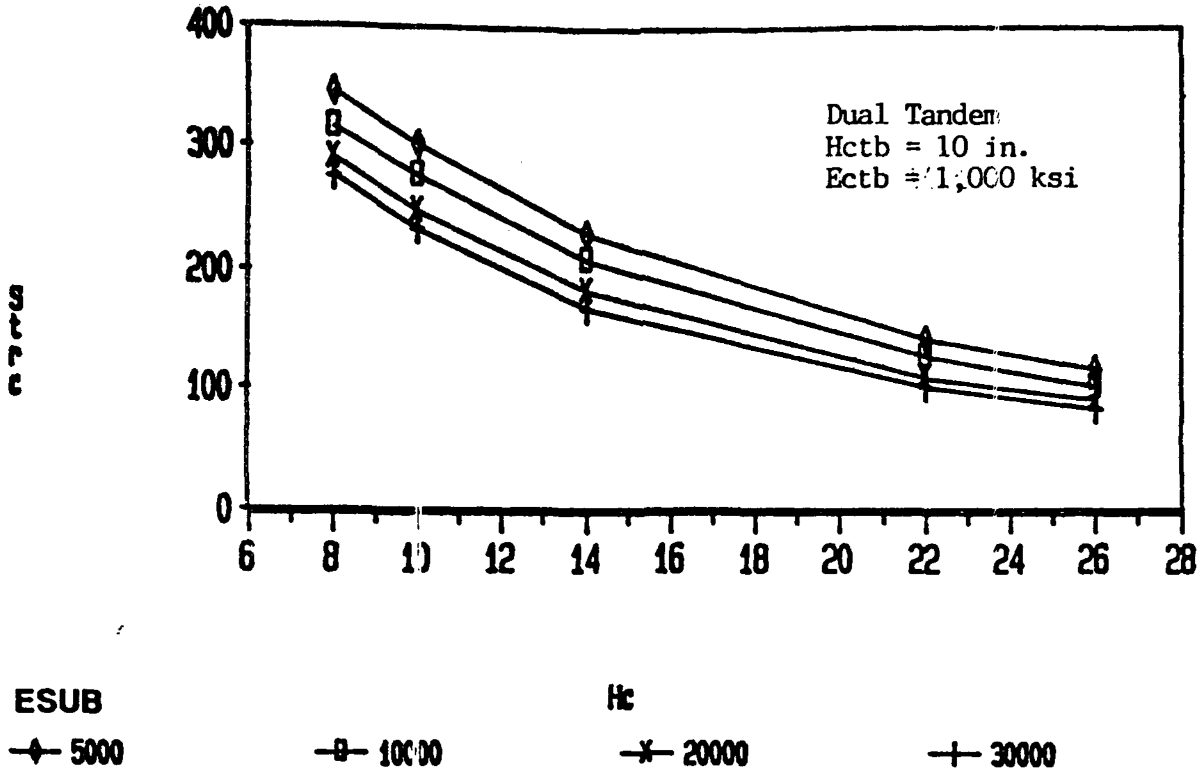

Figure B47. Relationship between concrete thickness and stress in the concrete for all subgrade moduli

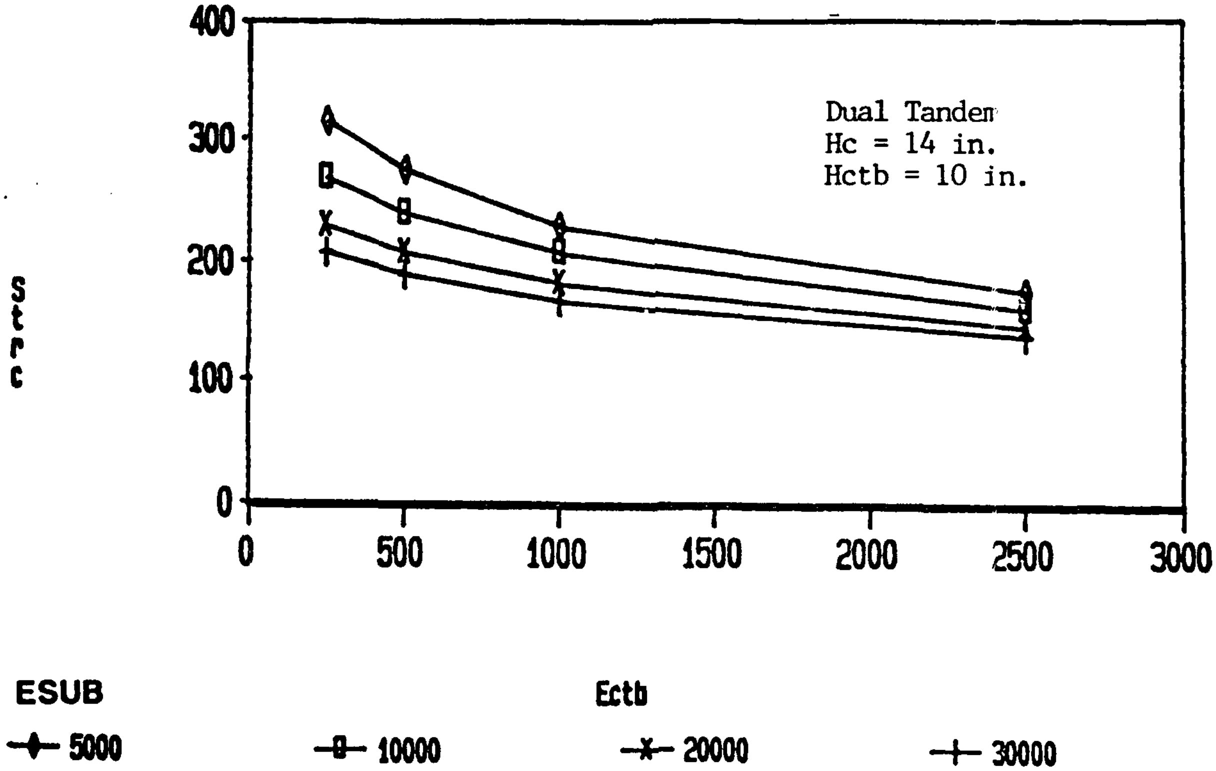

Figure B48. Relationship between CTB moduli and stress in the concrete for all subgrade moduli

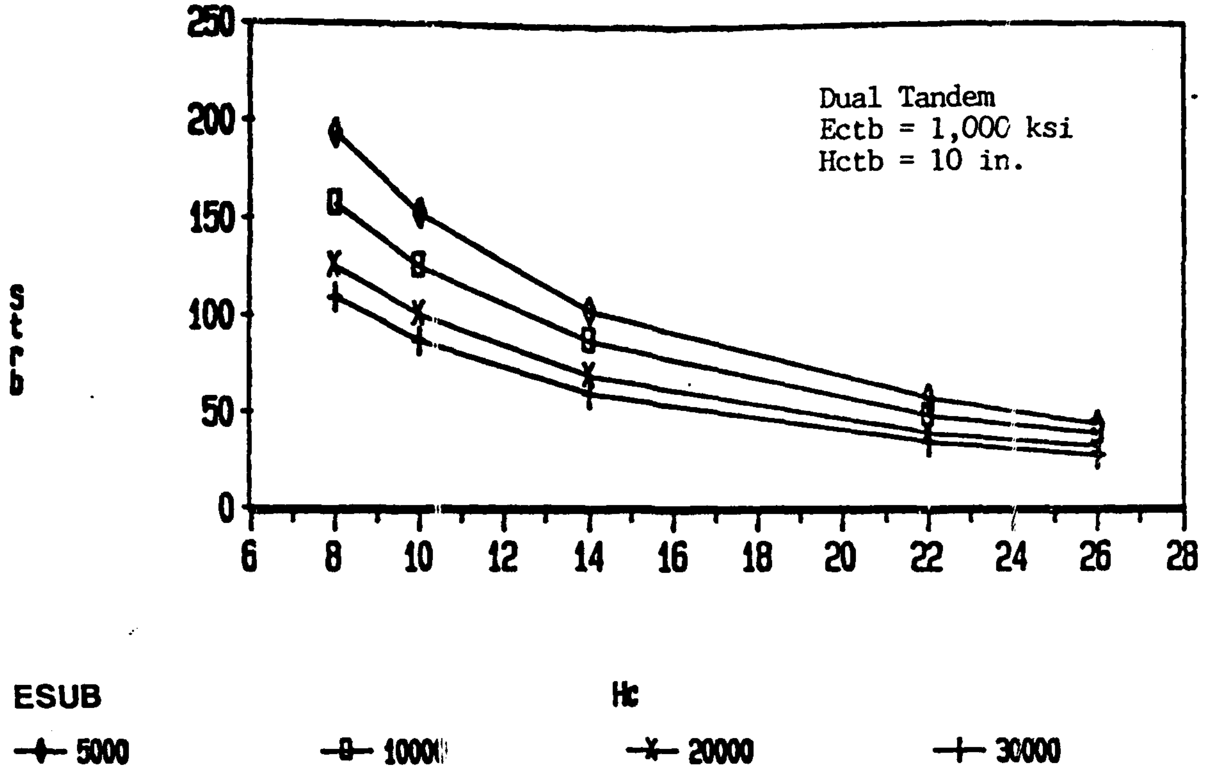

Figure B49. Relationship between concrete thickness and stress in the CTB for all subgrade moduli

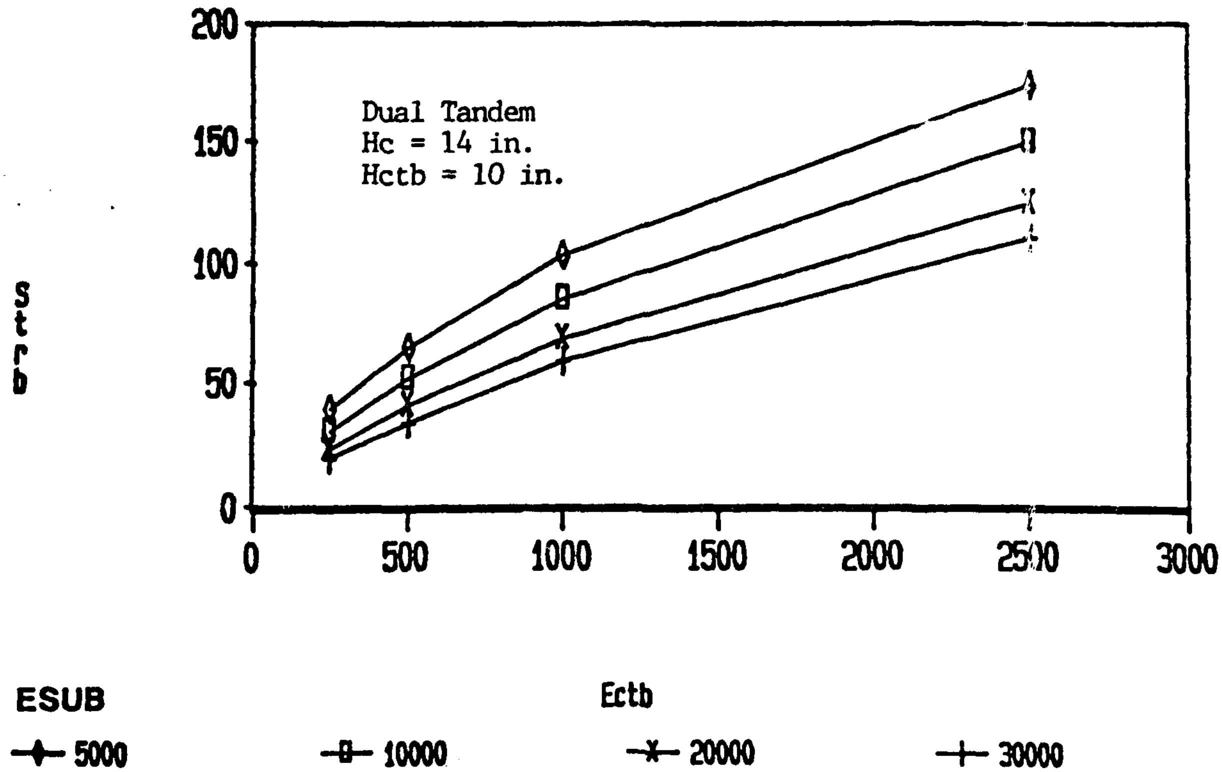

Figure B50. Relationship between CTB moduli and stress in the CTB for all subgrade moduli

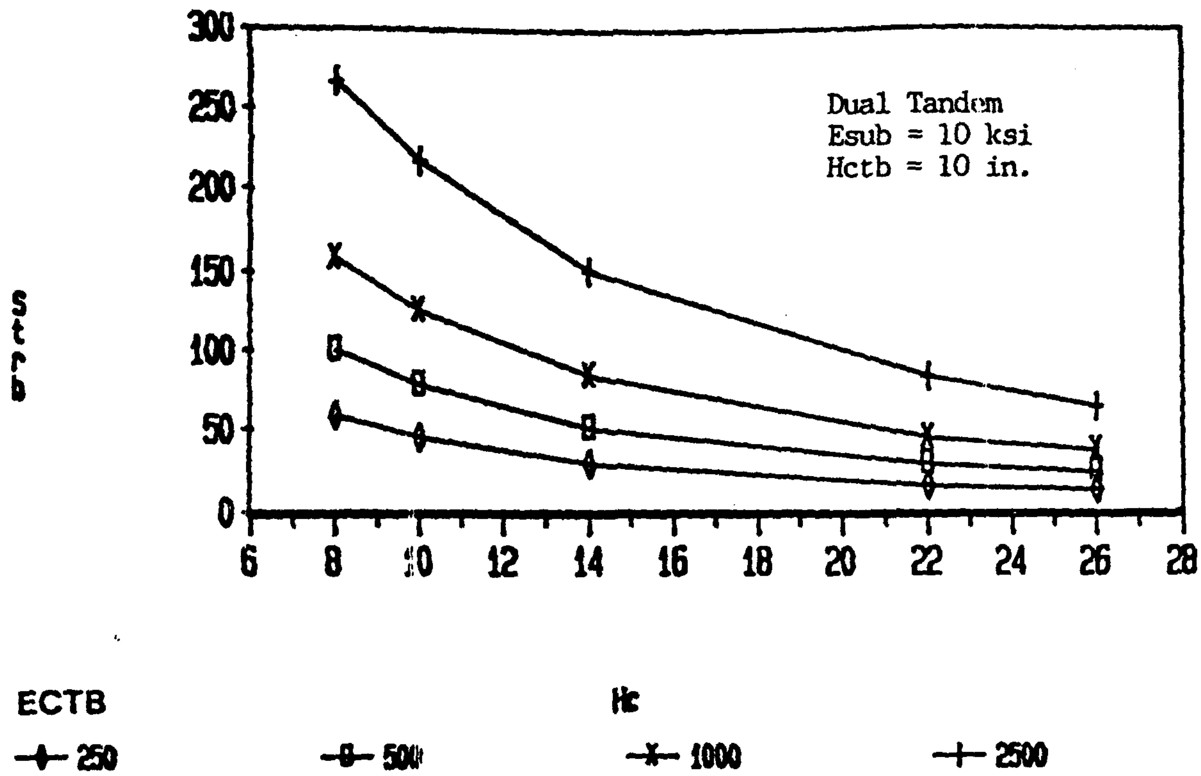

Figure B51. Relationship between concrete thickness and stress in the CTB for all CTB moduli

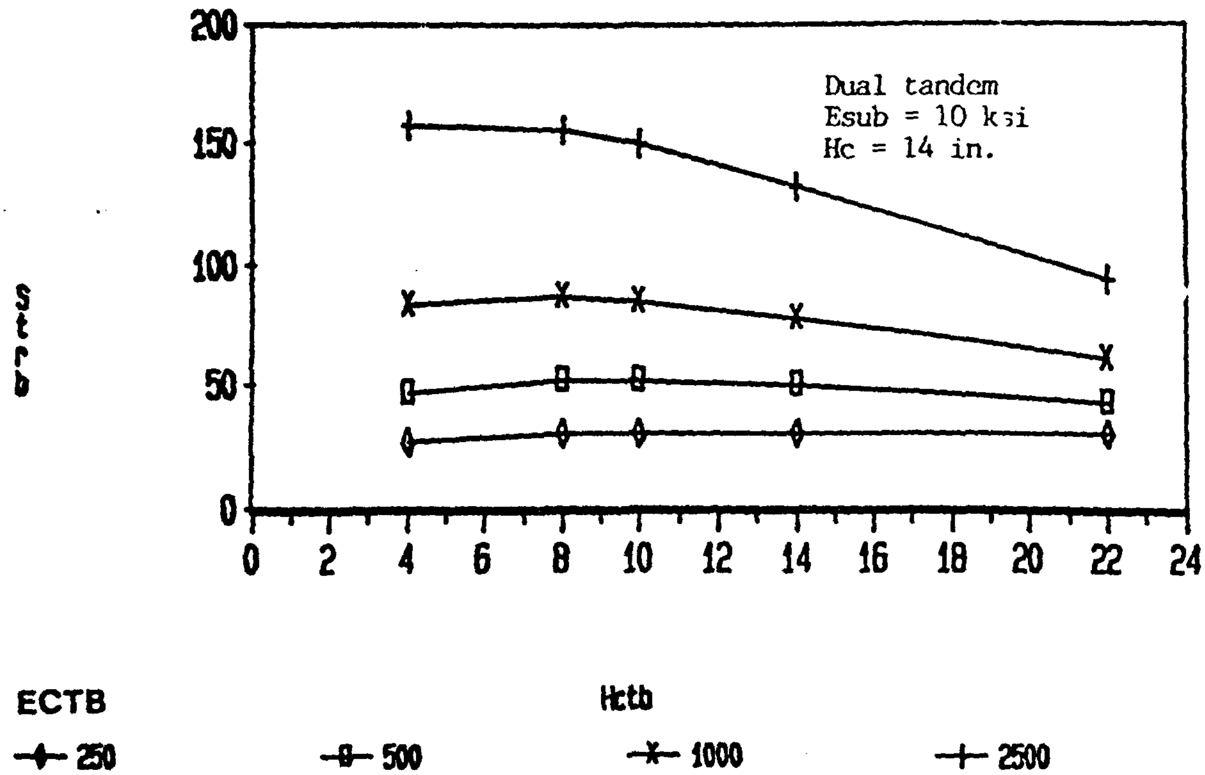

Figure B52. Relationship between CTB thickness and stress in the CTB for all CTB moduli

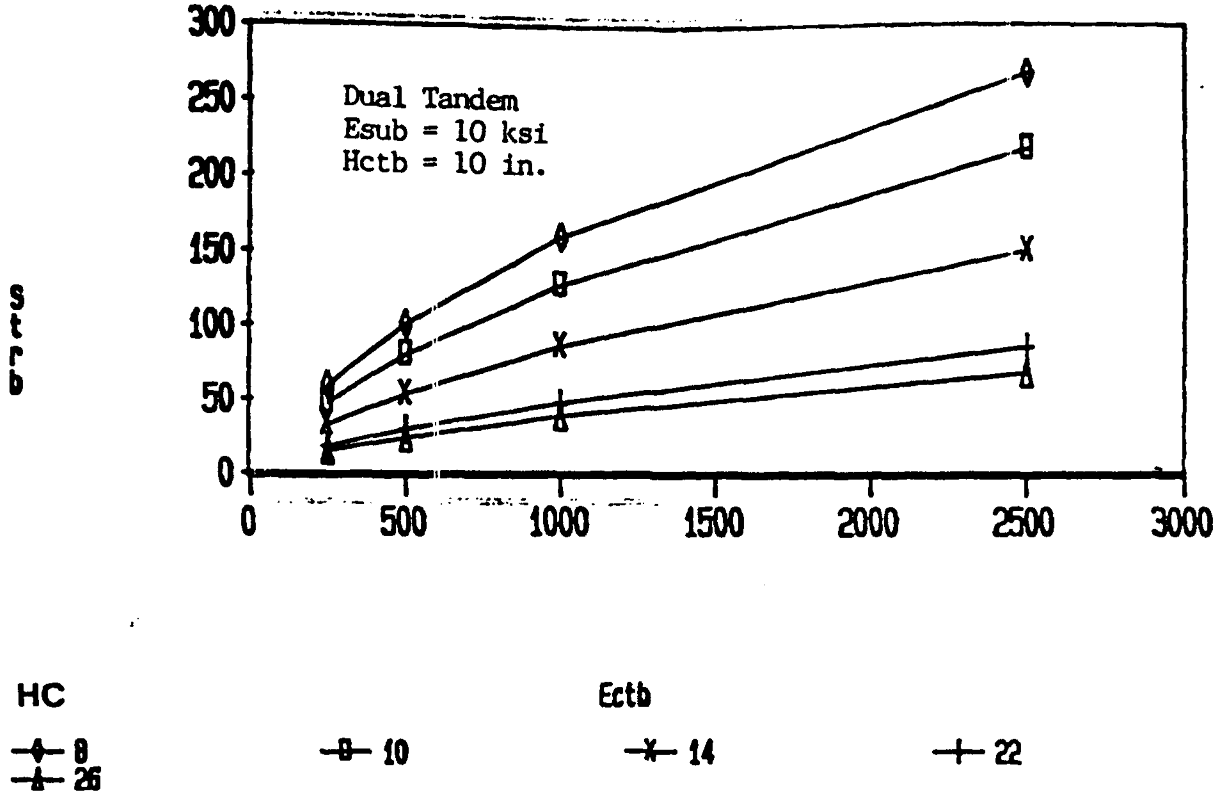

Figure B53. Relationship between CTB moduli and stress in the CTB for all concrete thicknesses

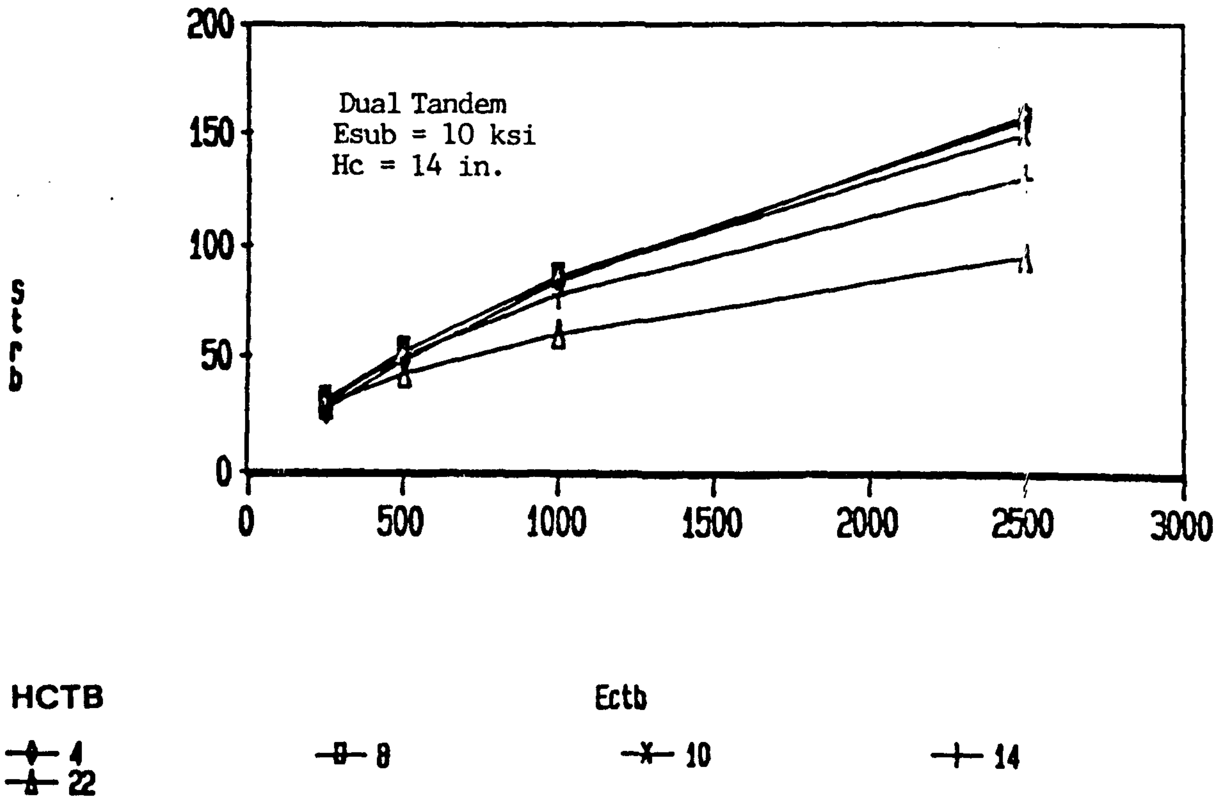

Figure B54. Relationship between CTB moduli and stress in the CTB for all CTB thicknesses

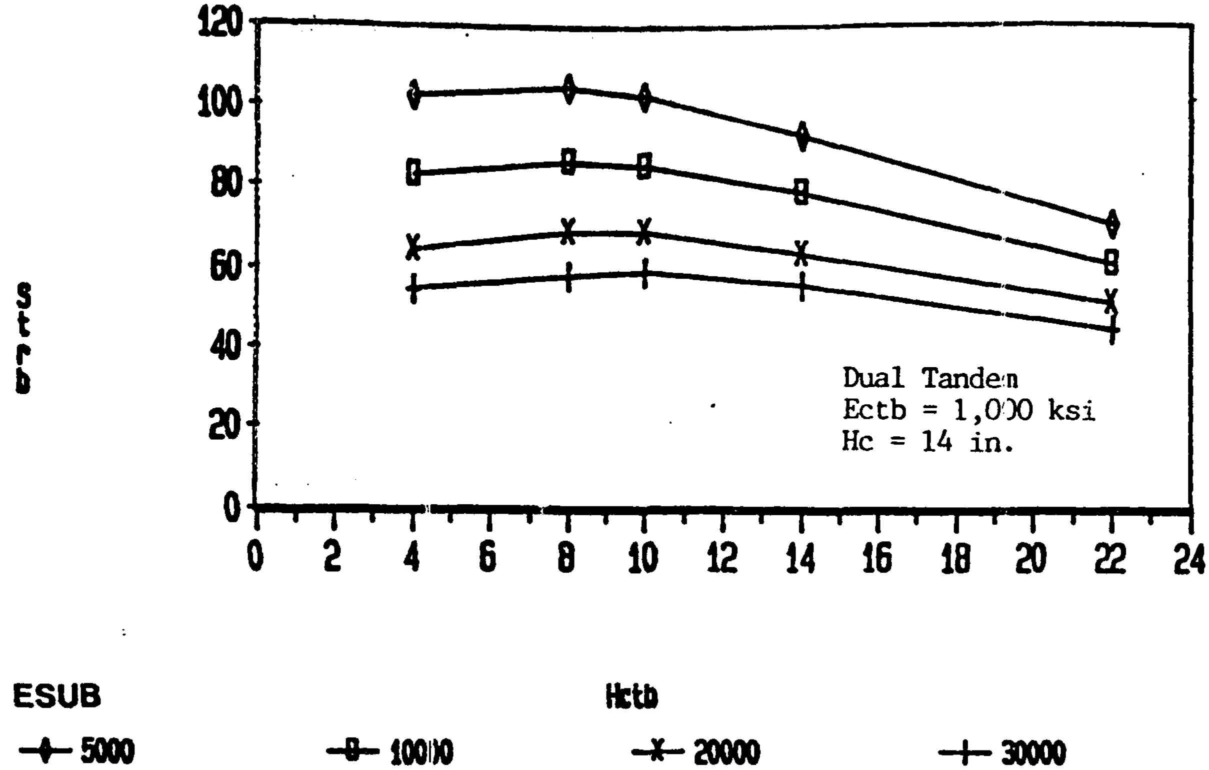

Figure B55. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

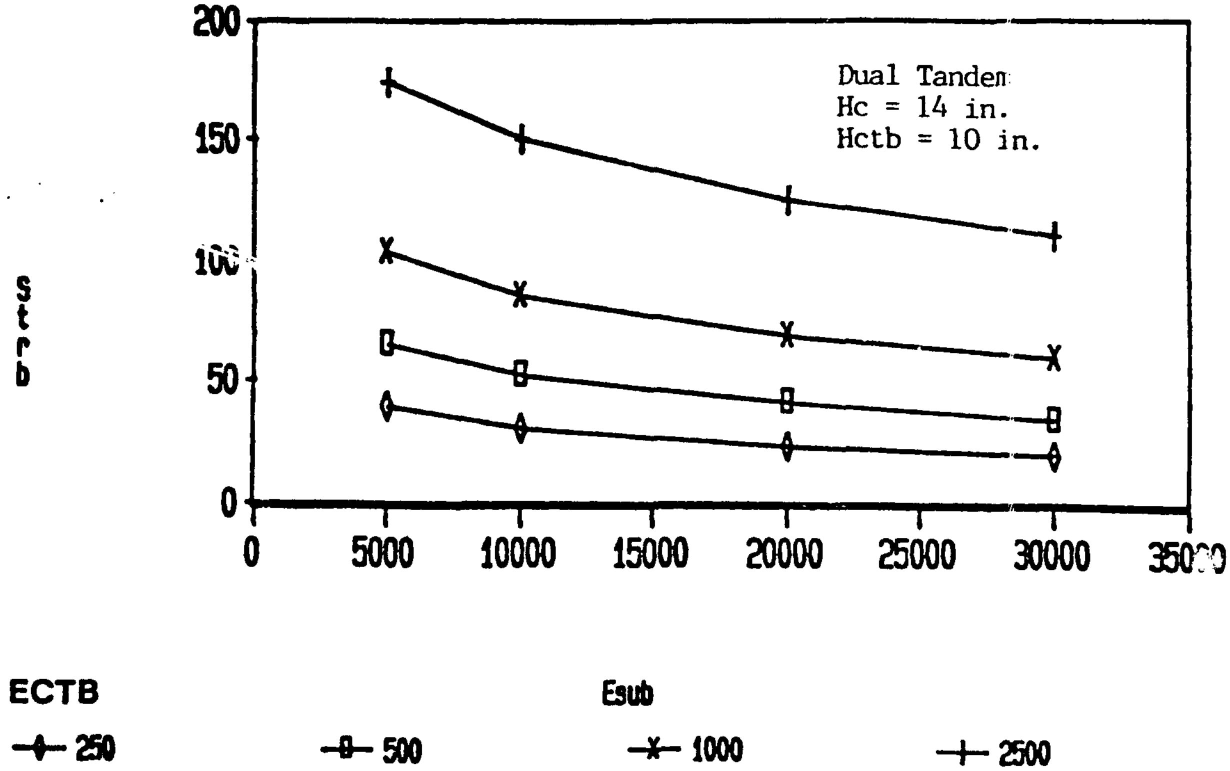

Figure B56. Relationship between subgrade moduli and stress in the CTB for all CTB moduli

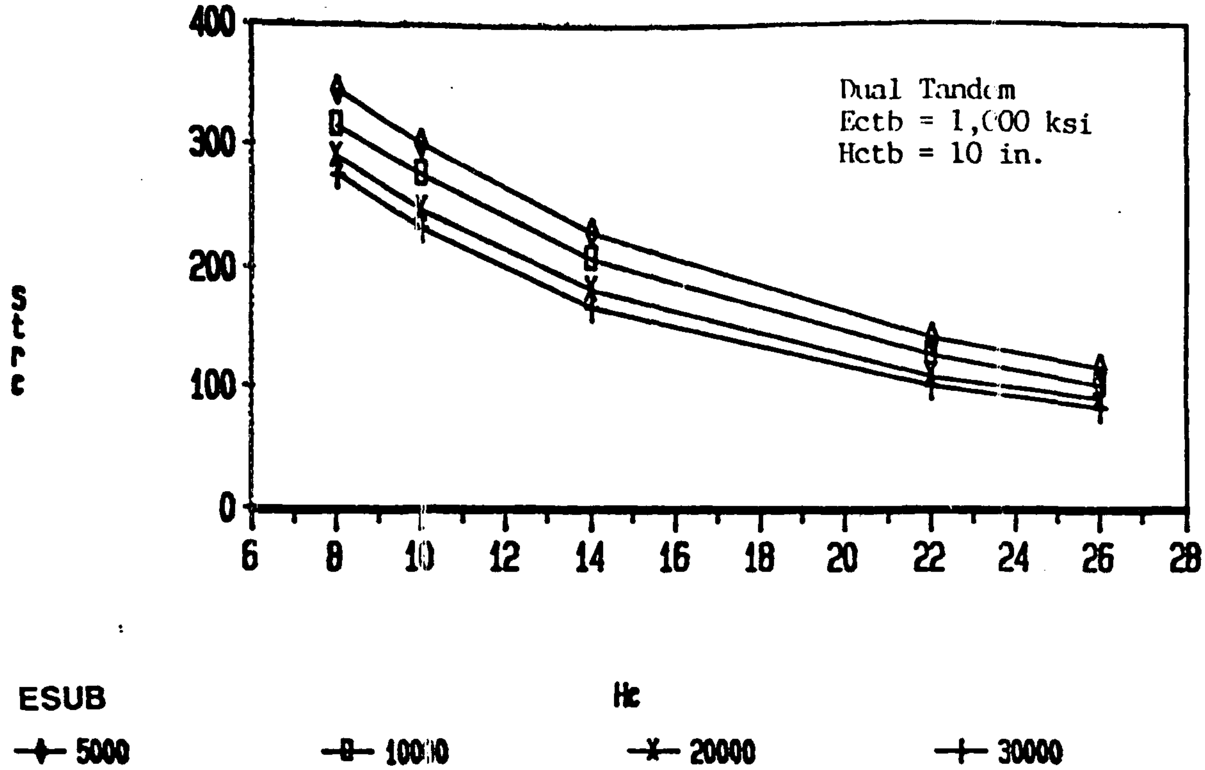

Figure B57. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli

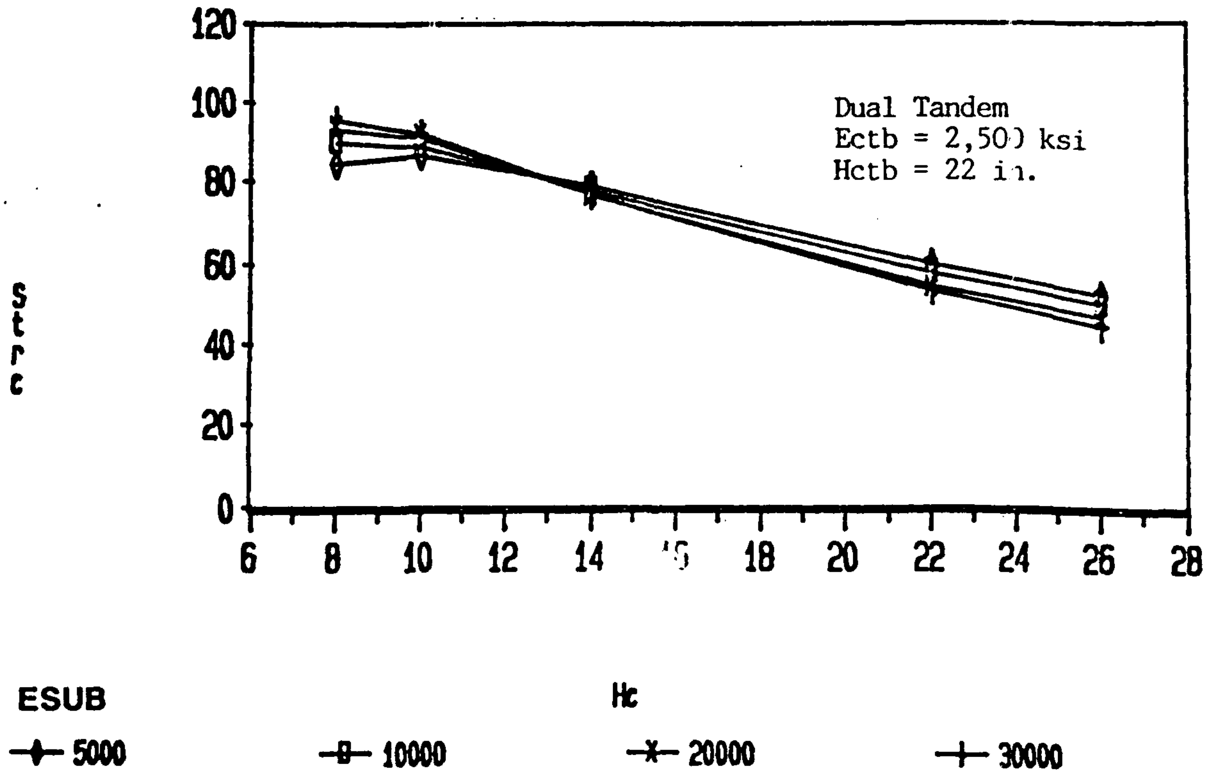

Figure B58. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli evaluated at the boundaries of the factorial

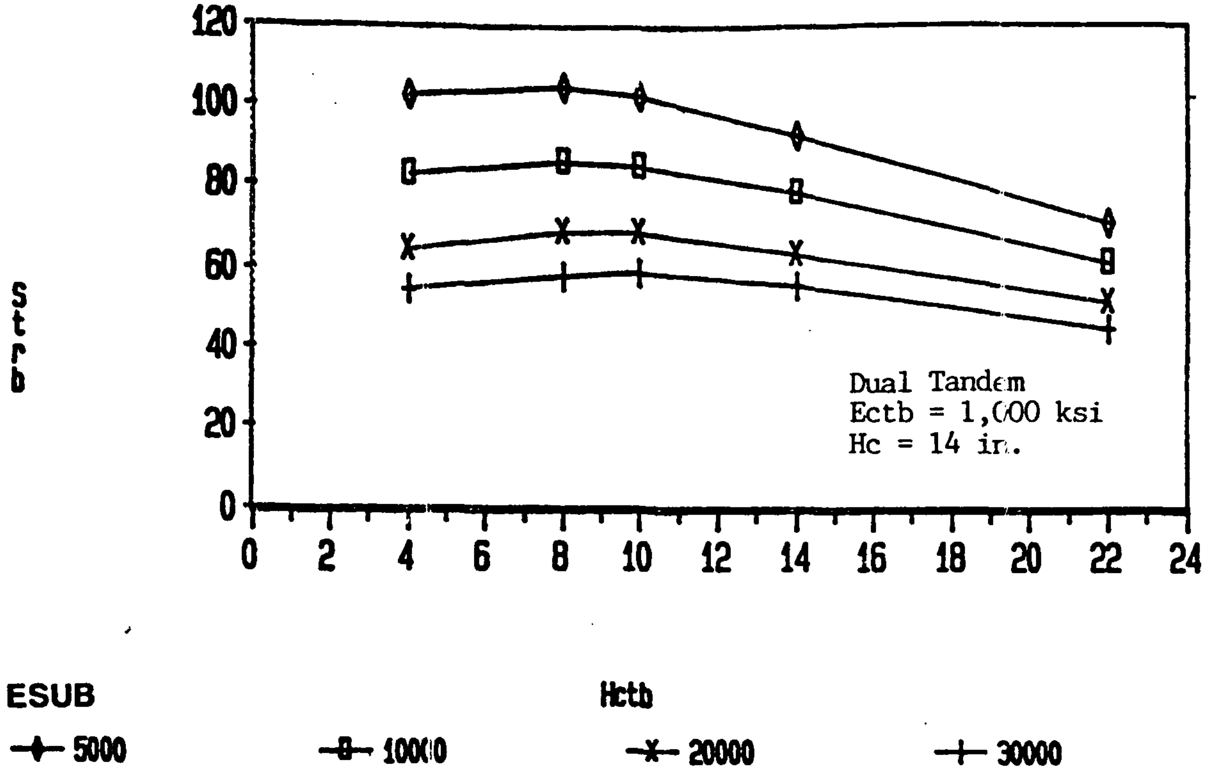

Figure B59. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

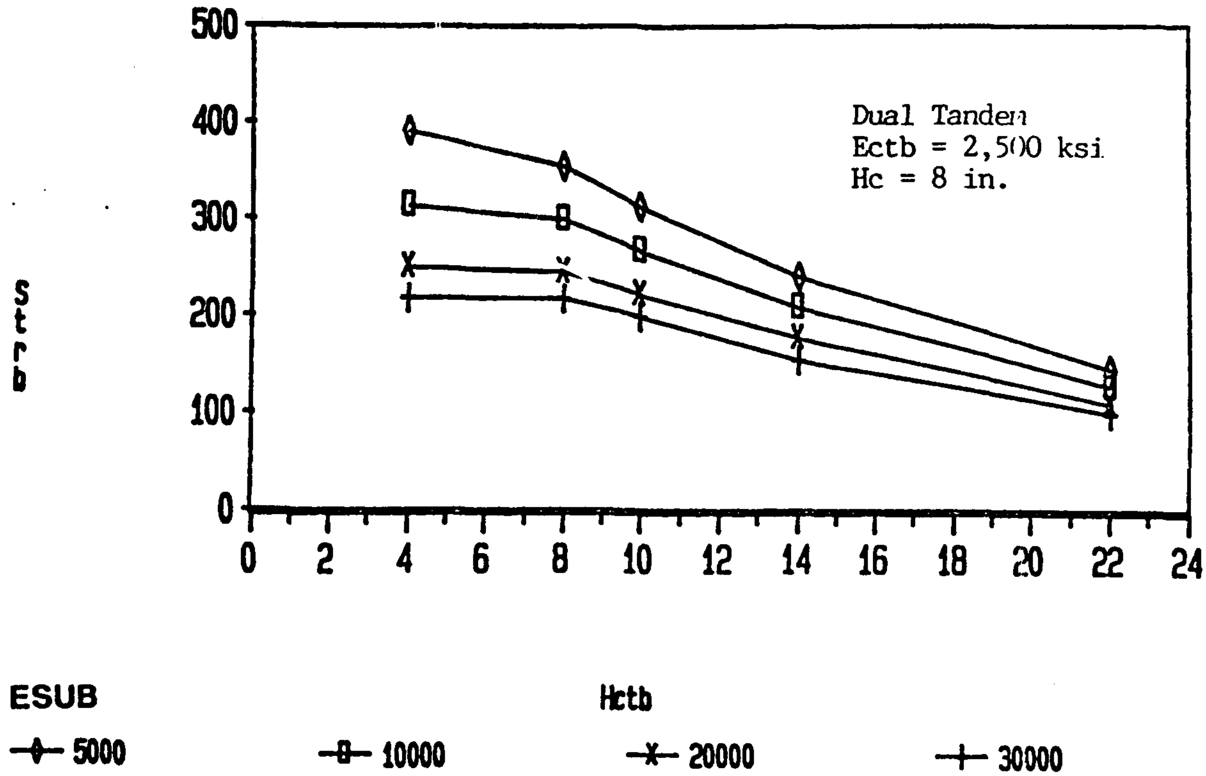

Figure B60. Relationship between CTB thickness and stress in the CTB for all subgrade moduli evaluated at the boundaries of the factorial

APPENDIX C

SOURCE CODES FOR CTBDES AND CTBEVL PROGRAMS

CTBDES PROGRAM

```
10 KEY OFF:CLS
20 LOCATE 10,5
30 PRINT "THIS PROGRAM PROVIDES A LIST OF THICKNESS COMBINATIONS
   OF CONCRETE"
40 PRINT "    SURFACE AND CEMENT TREATED BASE.  THE SELECTED
   THICKNESS COMBINATIONS"
50 PRINT "    ARE BASED ON ACHIEVING AN EQUIVALENT MAXIMUM TENSILE
   STRESS AT THE"
60 PRINT "    BOTTOM OF THE CONCRETE SURFACE LAYER.  STRESS RATIOS
   IN THE BASE ARE"
70 PRINT "    PROVIDED FOR EACH COMBINATIONS.  A STRESS RATIO OF
   0.5 OR LESS IS"
80 PRINT "    RECOMMENDED."
90 LOCATE 24,25
100 PRINT "PRESS ANY KEY TO CONTINUE"
110 A$=INKEY$
120 IF A$="" THEN GOTO 110 ELSE 130
130 CLS
140 LOCATE 5
150 PRINT "INPUT REQUIREMENTS INCLUDE SUBGRADE PROPERTY, THICKNESS
    OF CONCRETE"
160 PRINT "SURFACE LAYER AS DETERMINED BY FAA DESIGN PROCEDURE,
    LOAD CONDITION,"
170 PRINT "AND THE CEMENT TREATED BASE MATERIAL PROPERTY.  THE
    STRESSES USED"
180 PRINT "TO ACHIEVE THE EQUIVALENCY BETWEEN THE TWO PAVEMENT
    SYSTEM ARE"
190 PRINT "COMPUTED USING LINEAR REGRESSION EQUATIONS.  THE VALID
    RANGE OF"
200 PRINT "VARIABLES LISTED BELOW.  NO ERROR MESSAGES WILL BE
    PRINTED IF"
210 PRINT "THE SELECTED VARIABLE VALUE IS OUTSIDE THE VALID RANGE
    OF THE EQUATIONS."
220 LOCATE 13
230 PRINT "    SUBGRAGE RESILIENT MODULUS = 5 TO 30 KSI"
240 PRINT "    MODULUS OF SUBGRADE REACTION = 60 TO 240 PCI"
250 PRINT "    THICKNESS OF CONCRETE LAYER = 8 TO 26 INCHES"
260 PRINT "    THICKNESS OF CTB = 4 TO 22 INCHES"
270 PRINT "    LOAD CONDITION =SINGLE WHEEL GEAR, DUAL GEAR,"
280 PRINT "                      AND DUAL TANDEM GEAR"
290 PRINT "    CTB RESILIENT MODULUS = 250 TO 2,500 KSI"
300 PRINT "    CTB COMPRESSIVE STRENGTH = 1,200 TO 2,700 PSI"
310 LOCATE 24,25
320 PRINT "PRESS ANY KEY TO CONTINUE"
330 A$=INKEY$
340 IF A$="" THEN GOTO 330 ELSE 350
350 CLS
360 OPTION BASE 1:DIM A(3,7), B(3,13), C(3,13)
370 GOSUB 860
380 LOCATE 10
```

```
390 INPUT"DO YOU WANT TO SEND OUTPUT TO SCREEN, PRINTER, OR FILE
    (S, P,OR F)";C$
400 IF C$="S" OR C$="s" THEN 430
410 IF C$="f" OR C$="F" THEN GOTO 440
420 IF C$="p" OR C$="P" THEN GOTO 460 ELSE 390
430 OPEN "SCRN:" FOR OUTPUT AS #1:GOTO 470
440 INPUT"NAME OF YOUR OUTPUT FILE";STT$
450 OPEN STT$ FOR OUTPUT AS #1:GOTO 470
460 OPEN "LPT1" FOR OUTPUT AS #1
470 CLS
480 LOCATE 10
490 INPUT"WHICH SUBGRADE PROPERTY DO YOU WANT TO USE (K OR E)";A$
500 IF A$="K" OR A$="k" THEN GOTO 540
510 IF A$="E" OR A$="e" THEN GOTO 520 ELSE GOTO 490
520 INPUT"ENTER SUBGRADE RESILIENT MODULUS, E
    (KSI)";ESUB:ESUB=ESUB*1000
530 K=10^(((LOG(ESUB)/LOG(10))-1.415)/1.284): GOTO 560
540 INPUT"ENTER MODULUS OF SUBGRADE REACTION, K (PCI)";K
550 ESUB=10^(1.284*(LOG(K)/LOG(10))+1.415)
560 INPUT"WHICH CTB MATERIAL PROPERTY DO YOU WANT TO USE (FC OR
    E)";B$
570 IF B$="FC" OR B$="fc" THEN GOTO 610
580 IF B$="E" OR B$="e" THEN GOTO 590 ELSE GOTO 560
590 INPUT"ENTER MODULUS OF CTB (KSI)";ECTB:ECTB=ECTB*1000
600 UC=1091.2*EXP(3.596552E-07*ECTB):GOTO 630
610 INPUT"ENTER COMPRESSIVE STRENGTH OF CTB (PSI)";UC
620 ECTB=(LOG(UC)-LOG(1091.2))/3.596552E-07
630 INPUT"ENTER DESIGN CONCRETE THICKNESS OBTAINED FROM FAA
    PROCEDURE (IN.)";HCD
640 ER=4000000!/ESUB
650 L=(4000000!*(HCD^3)/(11.73*K))^.25
660 INPUT"ENTER GEAR TYPE (SW,DT,DW)";GT$
665 INPUT"ENTER AIRCRAFT GROSS LOAD, P (KIPS)";P:P=P*1000
670 CLS
680 IF C$="p" OR C$="P" OR C$="F" OR C$="f" THEN GOTO 690 ELSE
    GOTO 710
690 LOCATE 12,15
700 PRINT "PLEASE WAIT FOR OUTPUT FILE OR PRINTER"
710 PRINT #1,"SUBGRAGE PROPERTIES - ESUB  (KSI) = ",ESUB/1000
720 PRINT #1,"                      K     (PCI) = ",K
730 PRINT #1,"BASE PROPERTIES -     ECTB  (KSI) =",ECTB/1000
740 PRINT #1,"                      FC    (PSI) =",UC
750 PRINT #1, USING "& ##.##";"CONCRETE THICKNESS AS CALCULATED BY
    FAA DESIGN, HC (IN) = ",HCD
760 PRINT #1,"GEAR TYPE :",GT$
765 PRINT #1,"GROSS LOAD OF DESIGN AIRCRAFT, P (KIPS) = ",P/1000
770 FOR JK=1 TO 5:PRINT #1,"":NEXT JK
780  UC=1091.2*EXP(3.596552E-07*ECTB)
790 PRINT #1,"     DETERMINATION OF CONCRETE AND CTB THICKNESS
    COMBINATIONS"
800 PRINT #1,""
805 P1=0
810 IF GT$ ="SW" OR GT$="sw" THEN P1=84211!:J=1:GOTO 840 ELSE GOTO
    820
```

```
820 IF GT$ ="DW" OR GT$="dw" THEN P1=190000!:J=2:GOTO 840 ELSE
    GOTO 830
830 IF GT$ ="DT" OR GT$="dt" THEN P1=305263!:J=3:GOTO 840 ELSE
    GOTO 660
840 SNB=P/P1*(A(J,7)+A(J,1)*LOG(ESUB)+1/HCD^2*(A(J,3)*L+A(J,4)*K)
    +LOG(L)*(A(J,5)*HCD+A(J,2)*LOG(ESUB))+(A(J,6)*(1/HCD^3)))
850 GOTO 950
860 FOR I=1 TO 3
870 FOR J=1 TO 7
880 READ A(I,J)
890 NEXT J
900 NEXT I
910 DATA 79.87059,-20.83124,1043.40315,-
    28.99054,1.11244,33382.69811,-54.80360
920 DATA 70.87699,-13.20461,1886.23113,-35.41080,0.91015,0.0,-
    307.15867
930 DATA -104.54994,41.08126,1754.38235,31.44690,-1.86926,-
    74211.45618,-601.92659
940 RETURN
950 GOSUB 1400
960 GOSUB 1630
970 COUNT = 0:HL=0:HC=0:HCTB=0
980 HL = HL+10
990 HC=HC+8
1000 HCTB=HCTB+4
1005 PRINT #1," THICKNESS (IN)              STRESS (PSI)
     STRESS       ALLOWABLE"
1010 PRINT #1,"CONC.          CTB           PREDICTED  DESIGN     RATIO
     PASSES"
1020 PRINT #1,""
1030 ER1=4000000!/ECTB
1040 ER2=ECTB/ESUB
1050 COUNT=COUNT+1
1060 L1=((4000000!*HC^3)/(11.73*K))^.25
1070 L2=((ECTB*HCTB^3)/(11.73*K))^.25
1080 SCB1=B(J,13)+B(J,1)*LOG(L1)/L1+HC*LOG(L1)*(B(J,2)+B(J,5)*L2)
     +1/HC^2*(B(J,3)*L1+B(J,6)*ER1*L1+B(J,9)*L2+B(J,11)*K*(L1/L2)+
     B(J,8)*L2*L1)
1090 BB=1/HC^.33*LOG(L1/HC)*(HCTB/HC)^2*ER1^-.25
1100 SCB2=BB*(B(J,4)+B(J,7)*ER2+B(J,10)*L2+B(J,12)*(ER1/ESUB)^.25)
1110 SCB=P/P1*(SCB1+SCB2)
1120 IF COUNT >1000 THEN GOTO 1380
1130 IF (SCB-SNB)>2.5 THEN 1140 ELSE 1200
1140 HCTB=HCTB+HL
1150 IF HCTB<4 GOTO 1310
1160 HL=HL/2.5
1170 IF HL<.05 THEN HL=.05
1180 IF HCTB>22 THEN HC=HC+.5:HCTB=4:HL=10
1190 GOTO 1050
1200 IF (SNB-SCB)>2.5 THEN 1250 ELSE 1210
1210 GOSUB 1520
1220 PRINT #1,USING "##.#         ##.#         ####         ####
     #.###      ##.##^^^^";HC,HCTB,SCB,SNB,SR,N
1230 IF HC>26 GOTO 1310
```

```
1240 HC=HC+.5:HCTB=4:HL=10:GOTO 1050
1250 HCTB=HCTB-HL
1260 IF HCTB<4 GOTO 1310
1270 HL=HL/2.5
1280 IF HL<.05 THEN HL=.05
1290 IF HCTB>22 THEN HC=HC+.5:HCTB=4:HL=10
1300 GOTO 1050
1310 PRINT #1,"":PRINT #1,""
1320 PRINT #1,"FOR THE LAST ITERATION:"
1330 PRINT #1,USING "& ## &";"HCTB IS < 4 IN. - USE HCTB= 4 IN.
     AND HC=", HC,"IN."
1340 IF C$="S" OR C$="s" THEN 1360 ELSE 1350
1350 PRINT #1,CHR$(12)
1360 CLOSE #1
1370 END
1380 PRINT "NO CONVERGENCE: CHANGE MODULUS OF CTB"
1390 END
1400 FOR I=1 TO 3
1410 FOR KK=1 TO 13
1420 READ B(I,KK)
1430 NEXT KK
1440 NEXT I
1450 DATA 3152.60047,0.74036,1206.42011,40.11704,2.891281e-
     03,3.80009,0.02337
1460 DATA 0.0,-925.25867,0.45975,-5.58656,-44.92398,-307.75101
1470 DATA
     3903.81004,1.06777,1839.96268,79.37649,0.0,6.99535,0.03171,0.
     0
1480 DATA -1421.66496,0.73535,-10.42594,-195.49499,-388.66280
1490 DATA 543.62830,0.0,1304.04836,66.63757,0.0,5.63003,0.03013,-
     5.30015
1500 DATA -820.59149,0.36554,-7.26875,-139.49406,-41.35524
1510 RETURN
1520 SB1=(ER1/ESUB)^.25*(C(J,5)*HC*LOG(L1)+C(J,6)*ER2+C(J,10)*ER1+
     C(J,12))
1530 SB2=K/HC^2*(C(J,1)*HCTB^2+C(J,4)*L1/L2)
1540 SB3=LOG(L1)*HC*(C(J,3)*L1/HC^2+C(J,7)*(1/HC^.333*LOG(L1/HC)*(
     HB/HC)^2*ER1^-.25)+C(J,11)*LOG(L1)/L1)
1550 SB4=ER1*(C(J,2)+C(J,8)*L2)+C(J,9)*LOG(L1)/L1
1560 LOGSB=C(J,13)+SB1+SB2+SB3+SB4
1570 SB=P/P1*(EXP(LOGSB))
1580 UC=1091.2*EXP(3.596552E-07*ECTB)
1590 MR=UC/5
1600 SR=SB/MR
1610 N=10^((.972-SR)/8.250001E-02)
1620 IF SR<.5 THEN GOTO 1220 ELSE GOTO 1220
1630 FOR I=1 TO 3
1640 FOR N=1 TO 13
1650 READ C(I,N)
1660 NEXT N
1670 NEXT I
1680 DATA -1.54962E-04,-0.09001,0.32334,-0.02994,-0.0185,-
     6.82371E-03
```

```
1690 DATA -7.93621E-03,2.778992E-04,22.59014,0.47821,-0.15486,-
     22.51655,1.57794
1700 DATA -1.14871E-04,-0.08893,0.3387,-0.0235,-0.01829,-7.46144E-
     03
1710 DATA -7.78525E-03,5.404066E-04,20.06895,0.46020,-0.12404,-
     22.89465,1.92671
1720 DATA -9.69983E-05,-0.09306,0.36498,-0.02921,-9.29258E-03,-
     8.35922E-03
1730 DATA -7.471E-03,7.702747E-04,17.86815,0.45719,-0.08699,-
     23.87935,1.46192
1740 RETURN
```

CTBEVL PROGRAM

```
10 KEY OFF:CLS
20 LOCATE 10,5
30 PRINT "THIS PROGRAM PROVIDES A LIST OF THICKNESS COMBINATIONS
   OF CONCRETE"
40 PRINT "    SURFACE AND CEMENT TREATED BASE.  THE SELECTED
   THICKNESS COMBINATIONS"
50 PRINT "    ARE BASED ON ACHIEVING AN EQUIVALENT MAXIMUM TENSILE
   STRESS AT THE"
60 PRINT "    BOTTOM OF THE CONCRETE SURFACE LAYER.  STRESS RATIOS
   IN THE BASE ARE"
70 PRINT "    PROVIDED FOR EACH COMBINATIONS.  A STRESS RATIO OF
   0.5 OR LESS IS"
80 PRINT "    RECOMMENDED."
90 LOCATE 24,25
100 PRINT "PRESS ANY KEY TO CONTINUE"
110 A$=INKEY$
120 IF A$="" THEN GOTO 110 ELSE 130
130 CLS
140 LOCATE 5
150 PRINT "INPUT REQUIREMENTS INCLUDE SUBGRADE PROPERTY, THICKNESS
    OF CONCRETE"
160 PRINT "SURFACE LAYER AS DETERMINED BY FAA DESIGN PROCEDURE,
    LOAD CONDITION,"
170 PRINT "AND THE CEMENT TREATED BASE MATERIAL PROPERTY.  THE
    STRESSES USED"
180 PRINT "TO ACHIEVE THE EQUIVALENCY BETWEEN THE TWO PAVEMENT
    SYSTEM ARE"
190 PRINT "COMPUTED USING LINEAR REGRESSION EQUATIONS.  THE VALID
    RANGE OF"
200 PRINT "VARIABLES IS LISTED BELOW.  NO ERROR MESSAGES WILL BE
    PRINTED IF"
210 PRINT "THE SELECTED VARIABLE VALUE IS OUTSIDE THE VALID RANGE
    OF THE EQUATIONS."
220 LOCATE 13
230 PRINT "    SUBGRAGE RESILIENT MODULUS = 5 TO 30 KSI"
240 PRINT "    MODULUS OF SUBGRADE REACTION = 60 TO 240 PCI"
250 PRINT "    THICKNESS OF CONCRETE LAYER = 8 TO 26 INCHES"
260 PRINT "    THICKNESS OF CTB = 4 TO 22 INCHES"
270 PRINT "    LOAD CONDITION =SINGLE WHEEL GEAR, DUAL GEAR,"
280 PRINT "                     AND DUAL TANDEM GEAR"
290 PRINT "    CTB RESILIENT MODULUS = 250 TO 2,500 KSI"
300 PRINT "    CTB COMPRESSIVE STRENGTH = 1,200 TO 2,700 PSI"
310 LOCATE 24,25
320 PRINT "PRESS ANY KEY TO CONTINUE"
330 A$=INKEY$
340 IF A$="" THEN GOTO 330 ELSE 350
350 CLS
360 OPTION BASE 1:DIM A(3,7), B(3,13), C(3,13)
370 GOSUB 860
380 LOCATE 10
```

```
390 INPUT"DO YOU WANT TO SEND OUTPUT TO SCREEN, PRINTER, OR FILE
    (S, P,OR F)";C$
400 IF C$="S" OR C$="s" THEN 430
410 IF C$="f" OR C$="F" THEN GOTO 440
420 IF C$="p" OR C$="P" THEN GOTO 460 ELSE 390
430 OPEN "SCRN:" FOR OUTPUT AS #1:GOTO 470
440 INPUT"NAME OF YOUR OUTPUT FILE";STT$
450 OPEN STT$ FOR OUTPUT AS #1:GOTO 470
460 OPEN "LPT1" FOR OUTPUT AS #1
470 CLS
480 LOCATE 10
490 INPUT"WHICH SUBGRADE PROPERTY DO YOU WANT TO USE (K OR E)";A$
500 IF A$="K" OR A$="k" THEN GOTO 540
510 IF A$="E" OR A$="e" THEN GOTO 520 ELSE GOTO 490
520 INPUT"ENTER SUBGRADE RESILIENT MODULUS, E
    (KSI)";ESUB:ESUB=ESUB*1000
530 K=10^(((LOG(ESUB)/LOG(10))-1.415)/1.284): GOTO 560
540 INPUT"ENTER MODULUS OF SUBGRADE REACTION, K (PCI)";K
550 ESUB=10^(1.284*(LOG(K)/LOG(10))+1.415)
560 INPUT"WHICH CTB MATERIAL PROPERTY DO YOU WANT TO USE (FC OR
    E)";B$
570 IF B$="FC" OR B$="fc" THEN GOTO 610
580 IF B$="E" OR B$="e" THEN GOTO 590 ELSE GOTO 560
590 INPUT"ENTER MODULUS OF CTB, E (KSI)";ECTB:ECTB=ECTB*1000
600 UC=1091.2*EXP(3.596552E-07*ECTB):GOTO 630
610 INPUT"ENTER COMPRESSIVE STRENGTH OF CTB (PSI)";UC
620 ECTB=(LOG(UC)-LOG(1091.2))/3.596552E-07
630 INPUT"ENTER CONCRETE THICKNESS, HC (IN.), AS DETERMINED FROM
    FAA DESIGN";HCD
640 ER=4000000!/ESUB
650 L=(4000000!*(HCD^3)/(11.73*K))^.25
660 INPUT"ENTER GEAR TYPE (SW,DT,DW)";GT$
665 INPUT"ENTER AIRCRAFT GROSS LOAD, P (KIPS)";P:P=P*1000
670 CLS
680 IF C$="p" OR C$="P" OR C$="F" OR C$="f" THEN GOTO 690 ELSE
    GOTO 710
690 LOCATE 12,15
700 PRINT "PLEASE WAIT FOR OUTPUT FILE OR PRINTER"
710 PRINT #1,"SUBGRAGE PROPERTIES - ESUB  (KSI) = ",ESUB/1000
720 PRINT #1,"                      K     (PCI) = ",K
730 PRINT #1,"BASE PROPERTIES -     ECTB  (KSI) =",ECTB/1000
740 PRINT #1,"                      FC    (PSI) =",UC
750 PRINT #1, USING "& ##.##";"CONCRETE THICKNESS AS DETERMINED
    FROM FAA DESIGN, HC (IN) = ",HCD
760 PRINT #1,"DESIGN GEAR TYPE =",GT$
765 PRINT #1,"GROSS LOAD OF DESIGN AIRCRAFT, P (KIPS) = ",P/1000
770 FOR JK=1 TO 5:PRINT #1,"":NEXT JK
780  UC=1091.2*EXP(3.596552E-07*ECTB)
790 PRINT #1,"   DETERMINATION OF CONCRETE THICKNESS FOR A GIVEN
    BASE THICKNESS"
800 PRINT #1,"":PRINT #1,"":PRINT #1,""
810 IF GT$ ="SW" OR GT$="sw" THEN P1=84211!:J=1:GOTO 840 ELSE GOTO
    820
```

```
820 IF GT$ ="DW" OR GT$="dw" THEN P1=190000!:J=2:GOTO 840 ELSE
    GOTO 830
830 IF GT$ ="DT" OR GT$="dt" THEN P1=305263!:J=3:GOTO 840 ELSE
    GOTO 660
840 SNB=P/P1*(A(J,7)+A(J,1)*LOG(ESUB)+1/HCD^2*(A(J,3)*L+A(J,4)*K)+
    LOG(L)*(A(J,5)*HCD+A(J,2)*LOG(ESUB))+(A(J,6)*(1/HCD^3)))
850 GOTO 950
860 FOR I=1 TO 3
870 FOR J=1 TO 7
880 READ A(I,J)
890 NEXT J
900 NEXT I
910 DATA 79.87059,-20.83124,1043.40315,-
    28.99054,1.11244,33382.69811,-54.80360
920 DATA 70.87699,-13.20461,1886.23113,-35.41080,0.91015,0.0,-
    307.15867
930 DATA -104.54994,41.08126,1754.38235,31.44690,-1.86926,-
    74211.45618,-601.92659
940 RETURN
950 GOSUB 1390
960 GOSUB 1610
970 COUNT = 0:HL=0:HC=0:HCTB=0
980 HL = HL+5
990 HC=HC+8
1000 INPUT"ENTER KNOWN THICKNESS OF CTB";HCTB
1001 CLS
1005 PRINT #1,"":PRINT #1,"":PRINT #1,""
1009 PRINT #1,"   THICKNESS (IN)      STRESS (PSI)      STRESS
     ALLOWABLE"
1010 PRINT #1,"   CONC.      CTB     PREDICTED  DESIGN      RATIO
     PASSES"
1020 PRINT #1,""
1030 ER1=4000000!/ECTB
1040 ER2=ECTB/ESUB
1050 COUNT=COUNT+1
1060 L1=((4000000!*HC^3)/(11.73*K))^.25
1070 L2=((ECTB*HCTB^3)/(11.73*K))^.25
1080 SCB1=B(J,13)+B(J,1)*LOG(L1)/L1+HC*LOG(L1)*(B(J,2)+B(J,5)*L2)+
     1/HC^2*(B(J,3)*L1+B(J,6)*ER1*L1+B(J,9)*L2+B(J,11)*K*(L1/L2)+B
     (J,8)*L2*L1)
1090 BB=1/HC^.33*LOG(L1/HC)*(HCTB/HC)^2*ER1^-.25
1100 SCB2=BB*(B(J,4)+B(J,7)*ER2+B(J,10)*L2+B(J,12)*(ER1/ESUB)^.25)
1110 SCB=P/P1*(SCB1+SCB2)
1120 IF COUNT >1000 THEN GOTO 1370
1130 IF (SCB-SNB)>1! THEN 1140 ELSE 1200
1140 HC=HC+HL
1150 IF HC<8 GOTO 1340
1160 HL=HL/2.5
1170 IF HL<.01 THEN HL=.01
1180 IF HC >26 GOTO 1340
1190 GOTO 1050
1200 IF (SNB-SCB)>1! THEN 1240 ELSE 1210
1210 GOSUB 1510
```

```
1220 PRINT #1,USING "  ##.#      ##.#       ####       ####     #.###
     ##.##^^^^";HC,HCTB,SCB,SNB,SR,N
1230 GOTO 1330
1240 HC=HC-HL
1250 IF HC<8 GOTO 1340
1260 HL=HL/2.5
1270 IF HL<.01 THEN HL=.01
1280 IF HC>26 THEN GOTO 1340
1290 GOTO 1050
1300 PRINT #1,"":PRINT #1,""
1310 PRINT #1,"FOR THE LAST ITERATION:"
1320 PRINT #1,USING "& ## &";"HCTB IS < 4 IN. - USE HCTB= 4 IN.
     AND HC=", HC,"IN."
1330 IF C$="S" OR C$="s" THEN 1350 ELSE 1340
1340 PRINT #1,CHR$(12)
1350 CLOSE #1
1360 END
1370 PRINT "NO CONVERGENCE: CHANGE MODULUS OF CTB"
1380 END
1390 FOR I=1 TO 3
1400 FOR KK=1 TO 13
1410 READ B(I,KK)
1420 NEXT KK
1430 NEXT I
1440 DATA 3152.60047,0.74036,1206.42011,40.11704,2.891281e-03,
     3.80009,0.02337
1450 DATA 0.0,-925.25867,0.45975,-5.58656,-44.92398,-307.75101
1460 DATA 3903.81004,1.06777,1839.96268,79.37649,0.0,6.99535,
     0.03171,0
1470 DATA -1421.66496,0.73535,-10.42594,-195.49499,-388.66280
1480 DATA 543.62830,0.0,1304.04836,66.63757,0.0,5.63003,0.03013,-
     5.30015
1490 DATA -820.59149,0.36554,-7.26875,-139.49406,-41.35524
1500 RETURN
1510 SB1=(ER1/ESUB)^.25*(C(J,5)*HC*LOG(L1)+C(J,6)*ER2+C(J,10)*ER1+
     C(J,12))
1520 SB2=K/HC^2*(C(J,1)*HCTB^2+C(J,4)*L1/L2)
1530 SB3=LOG(L1)*HC*(C(J,3)*L1/HC^2+C(J,7)*(1/HC^.333*LOG(L1/HC)*(
     HB/HC)^2*ER1^-.25)+C(J,11)*LOG(L1)/L1)
1540 SB4=ER1*(C(J,2)+C(J,8)*L2)+C(J,9)*LOG(L1)/L1
1550 LOGSB=C(J,13)+SB1+SB2+SB3+SB4
1560 SB=P/P1*EXP(LOGSB)
1570 UC=1091.2*EXP(3.596552E-07*ECTB)
1580 MR=UC/5
1590 SR=SB/MR
1595 N=10^((.972-SR)/8.250001E-02)
1600 IF SR<.5 THEN GOTO 1220 ELSE GOTO 1220
1610 FOR I=1 TO 3
1620 FOR N=1 TO 13
1630 READ C(I,N)
1640 NEXT N
1650 NEXT I
1660 DATA -1.54962E-04,-0.09001,0.32334,-0.02994,-0.0185,-
     6.82371E-03
```

```
1670 DATA -7.93621E-03,2.778992E-04,22.59014,0.47821,-0.15486,-
     22.51655,1.57794
1680 DATA -1.14871E-04,-0.08893,0.3387,-0.0235,-0.01829,
     -7.46144E-03
1690 DATA -7.78525E-03,5.404066E-04,20.06895,0.46020,-0.12404,-
     22.89465,1.92671
1700 DATA -9.69983E-05,-0.09306,0.36498,-0.02921,-9.29258E-03,-
     8.35922E-03
1710 DATA -7.471E-03,7.702747E-04,17.86815,0.45719,-0.08699,-
     23.87935,1.46192
1720 RETURN
```